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FINAL REPORT

BLM Contract No. AA551-CT8-34

Physical Oceanographic Model Evaluation for the South Atlantic OCS Region

Submitted to:

U. S. Department of the Interior
Bureau of Land Management
Washington, D.C. 20240

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TABLE OF CONTENTS

Page

1.0 INTRODUCTION....1

1.1 THE ROLE OF MODELS IN THE BLM PROGRAM....4
  1.1.1 BLM Model Requirements in General....4
  1.1.2 Specific Requirements for the SAOS Region....13

1.2 STUDY METHODOLOGY....19

2.0 QUALITATIVE EVALUATION....23

2.1 SURFACE TRAJECTORY MODEL EVALUATION....24
  2.1.1 Special Considerations....25
    2.1.1.1 Spreading....25
    2.1.1.2 Advection....27
    2.1.1.3 Evaporation....33
    2.1.1.4 Dissolution....38
    2.1.1.5 Emulsification....38
    2.1.1.6 Sedimentation....39
    2.1.1.7 Auto-Oxidation....40
    2.1.1.8 Biodegradation....41
    2.1.1.9 Summary of Special Considerations....42
  2.1.2 Detailed Qualitative Evaluation of Selected Surface Trajectory Models....44
    2.1.2.1 Title: Mathematical Model of the Behavior of Oil Spills on Water with Natural and Chemical Dispersion....44
    2.1.2.2 Title: Prediction of Oil Slick motions in Narragansett Bay....45
    2.1.2.3 Title: The Use of a Diagnostic Circulation Model for Oil Trajectory Analysis....46
    2.1.2.4 Title: Monte Carlo Simulation of Oil Slick Movement....47
    2.1.2.5 Title: Random Drift of an Idealized Oil Patch...48
    2.1.2.6 Title: SLIKTRAK....49
    2.1.2.7 Title: OILSIM....51
    2.1.2.8 Title: An Oilspill Risk Analysis for the South Atlantic Outer Continental Shelf Lease Area....52

2.2 WATER COLUMN MODEL EVALUATIONS....53
  2.2.1 Special Considerations....53
  2.2.2 Detailed Qualitative Evaluation of Selected Interior Water Column Models....56

2.3 BOTTOM AND SEDIMENT TRANSPORT MODEL EVALUATION....77
  2.3.1 Special Considerations....78
  2.3.2 Detailed Qualitative Evaluation of Selected Bottom and Sediment Transport Models...86

TABLE OF CONTENTS (cont'd)

2.4 A LITERATURE REVIEW OF WAVES, CURRENTS AND WAVE-CURRENT FORCES...92
  2.4.1 Introduction...92
  2.4.2 Waves ...92
    2.4.2.1 Wave Theories...92
    2.4.2.2 Generation of Wind Waves...93
    2.4.2.3 Wave Prediction...94
    2.4.2.4 Determination of Extreme Waves...96
  2.4.3 Wave Current Interaction...96
    2.4.3.1 Waves on Currents Uniformly Distributed with Depth...97
    2.4.3.2 Waves on Currents Varying with Depth...98
  2.4.4 Wave-Current Forces...99
    2.4.4.1 Forces on Small Bodies...99
    2.4.3.2 Forces on Large Bodies...102

3.0 QUANTITATIVE MODEL EVALUATION...105

3.1 BACKGROUND ...105

3.2 QUANTITATIVE MODEL EVALUATION TECHNIQUES AND EXAMPLE...106
  3.2.1 Relative Error (Skill Computation)...106
  3.2.2 Absolute Error (R_A)...109
  3.2.3 Standard Coherency Analysis...109
  3.2.4 Linear Regression Techniques...112

3.3 COMPARISONS OF MODEL COMPUTATIONS AND FIELD OBSERVATIONS REPORTED IN THE LITERATURE...112
  3.3.1 Simon's (1975) Model of Lake Ontario...113
  3.3.2 Bennett's (1977) Model of Lake Ontario...113
  3.3.3 Hamilton and Rattray's 1978 Model of Upwelling on a Continental Shelf...114

4.0 ASSESSMENT OF ADEQUACY OF DATA BASE...116

4.1 HYDROGRAPHY...116

4.2 METEOROLOGICAL DATA...142
  4.2.1 Meteorological Data Sources and Ships of Opportunity Data Analysis...142
  4.2.2 Relationship Between Winds Observed at the Coast and Offshore...173
    4.2.2.1 Comparison of Observed Winds...173
    4.2.2.2 Data Analysis...175
    4.2.2.3 Year Long Statistics...178
    4.2.2.4 Seasonal Variability...190
    4.2.2.5 Recommendations...197

5.0 CONCLUSIONS AND RECOMMENDATIONS...199

5.1 OVERALL ADEQUACY OF EXISTING MODELS TO MEET BLM OBJECTIVES FOR THE SAOS REGION...199

TABLE OF CONTENTS (cont'd)

5.2 RECOMMENDATIONS 200
5.2.1 Recommendations for Bottom and Sediment Transport Modeling........200
5.2.2 Recommendations for Water Column Modeling................202
5.2.3 Recommendations for Surface Trajectory Modeling..........204
5.2.4 Recommendations for Ocean-Structure Interaction Modeling..........208

APPENDIX A - GEOSPECIFIC ASPECTS OF THE SOUTH ATLANTIC OCS REGION

A.1 GEOSPECIFIC ASPECTS OF THE SOUTH ATLANTIC OCS REGION............A-1
A.1.1 The Role of the Gulf Stream..............................A-1
A.1.2 Meteorological Forcing, Coastal Sea Level and Implications for Currents on the Shelf....A-11
A.1.3 Shelf Variability at Frequencies Higher Than Half Cycle/Day (Tidal Forces).......A-20
A.1.4 Thermohaline Circulation.................................A-36
A.1.5 Circulation Over the Blake Plateau.......................A-43

APPENDIX B - LIST OF PUBLISHED AND UNPUBLISHED SOURCES REVIEWED..........B-1

LIST OF FIGURES AND TABLES

			Page
Figure	1-1	Physical Oceanographic Model Evaluation Tasks	2
	1-2	Relationship Between Physical Models and the DOI-BLM OCS Decisionmaking Process -- The Commercial Fishing Industry as an Example (from BLM, 1978, Study Design for Resources Management Decisions).	9
	1-3	Relationship of Physical Oceanographic Circulation Models Output and Policy Decisions	10
	1-4	Impact Decision Mechanism	12
	1-5	The South Atlantic Outer Continental Shelf Study Area	14
	1-6	Tracts Offered for Lease in South Atlantic OCS Sale 43	16
Figure	2-1	The Size (ℓ) of an Oil Slick as a Function of Time (t) for a 9.08×10^6 Kilogram Spill. (from Fay, 1969).	26
	2-2	The Comparison Between Observed Slicks and Slick Outline	28
	2-3	Example of Irregular Spreading of Spilled Oil	29
Table	2-1	Comparison of Laboratory and Field Studies of Wind Induced Surface Drift	32
Figure	2-4	Example of Oil Spill Trajectory Results for a Spill Site Near the Center of the Proposed Lease Area: Summer	34
	2-5	Probability that if an Oil Spill Occurs in the South Atlantic Lease Area, It Will Reach a Particular Geographic Location	35
	2-6	Projected Cumulative Distribution of Petroleum Residues on South Atlantic Beaches Resulting from Small Scale, Chronic Spillage During the Production Life of the Lease Area.	36
Figure	3-1	Comparison of Calculated and Measured Mean Current Vectors	107
	3-2	Comparison of Timeseries of Bottom Currents Derived by Model and Actually Observed	108
	3-3	Example of Absolute Error	110
	3-4	Example of Frequency Distributions of Diagnostic/Predictive Models in Phase and Coherency	111
	3-5a	Comparison of Eastward Current Velocity Components at 15m	115
	3-5b	Comparison of u and v Velocity Profiles	115
Table	4-1	Specifications for Oceanographic Data Types Available at NODC	117
Figures thru	4-1 4-4		120, thru 135
	4-5	Typical Approximately Scaled Model Grid for a Northern Sub-Region of the SAOS	137
	4-6	Location of National Weather Service Observation Stations	143
	4-7	Location of Meteorological Monitoring Stations along the North Carolina Coast	144
Figure thru	4-8 4-19	Wind Stress Observation Counts January thru December	147 thru 159
 thru	4-20 4-31	Mean Wind - January thru December	160 thru 171

LIST OF FIGURES AND TABLES (cont'd)

4-32 September Mean Wind Calculated Using Three-Year Wind Velocity Records from all Sources 172
4-33 Observed Coastal and Buoy Sticks and Components 174
4-34 Component Spectra 179
4-35 Rotary Spectra 181
Table 4-2 Means and Variances Averaged Over the Year 180
Figure 4-36 Ordinary Coherence Squared and Phase 182
4-37 Partial and Multiple Coherence Squared 184
4-38 Transfer Function Amplitude and Phases for Estimating Offshore Wind Velocity Components from Coastal Wind Velocity Component 186
4-39 A Comparison Between Observed and Estimated Offshore Wind Velocity Component 188
4-40 A Comparison Between Low Pass Filtered Observed and Estimated Wind Velocity Components and Vectors 189
4-41 A Contour Plot of the Base 10 Logarithm of the v and u Wind Velocity Component Kinetic Energy Density Spectra as a Function of Frequency and Time at the Coast 191
4-42 A Contour Plot of the Base 10 Logarithm of the v and u Wind Velocity Component Kinetic Energy Density Spectra as a Function of Frequency and Time at the Offshore Buoy 192
4-43 Contour Plots of the Maximum and Minimum Coherencies Squared 194
4-44 Same Caption as Figure 4-43, only for the Offshore Buoy 196
4-45 The Multiple Squared Coherence as a Function of Frequency and Time Between v_B or u_B and the Coastal Component v_C and u_C 198

Figure A-1 Map of the Gulf Stream Showing Eddys and Filaments A-2
A-2 Current Vector Diagram Showing Passage of a Spin-Off Eddy Attached to a Gulf Stream Meander A-4
A-3 Temperature Section St. Augustine South 14 April 1977 A-7
A-4 Cross-Spectra of u and v Components A-10
Table A-1 Tidal Constituents in Onslow Bay during Summer 1976 A-23
Figure A-5a thru A-5i Energy Fraction vs. Frequency A-24 thru A-30
Figure A-6a thru A-6d Energy Fraction Depicting Percent of Energy in Bands Less Than and Greater Than 40 Hours, Offshore Savannah (Lee, 1979) A-31 thru A-34
A-7 Tidal Elipses for Summer, 1976 A-35
A-8 Savannah Section, T. N. GILL Cruises A-39
A-9 Location of Moorings for Various Oceanographic Measurements in the SAOS Region A-41
Table A-2 Station Location & Duration for Current Meter & Bottom Mounted Pressure Sensors in the South Atlantic Bight A-42
A-10a Volume Transport as a Function of Distance A-44
A-10b Annual Variations in Current Speeds of the Gulf Stream A-44
A-11 Generalized Bottom Currents, Microphysiography, and Sediment Cores from the Blake Plateau A-45

1.0 INTRODUCTION

For twelve months, JAYCOR personnel were under contract to the Bureau of Land Management (BLM) to conduct an evaluation of physical oceanographic models that could have applicability to the South Atlantic Outer Continental Shelf (SAOS) area. The objectives of this evaluation were to determine:

- which models, if any, were best suited to the BLM program needs in assessing the distribution of pollutants resulting from offshore activities and in assessing the probability of occurrence of circumstances hazardous to offshore structures;
- which models best fit the physics of the SAOS Region;
- the sensitivity of various models to data input; and
- the quantity and quality of existing input data to drive the models.

More than twelve-hundred papers have been reviewed in a three step process: semi-qualitative, detailed qualitative, and quantitative. All of the models, and the related background material are included in Appendix B of this report. This appendix includes a designation for each citation indicating the level at which the material reviewed was useful for this project. It should be emphasized that this model evaluation was done in the context of the South Atlantic OCS Region, and the results are not necessarily applicable to all OCS regions, although a significant portion of the information is transferrable to other similar areas. The tasks designed to achieve the project objectives are shown in Figure 1-1.

One of the remaining pieces for the SAOS Environmental Studies Program was the means for interfacing the large amount of physical oceanographic data being collected with the geological oceanographic data in the predictive environmental assessments to be conducted by the Department of the Interior. In this regard, the products of this evaluation were designed to be:

- A summary of the models reviewed, including the physics which they are capable of reproducing; approximations parameterization, and boundary conditions involved; and, most importantly, their relative expected accuracies when applied to the SAOS Region. This summary was

TASK 1. Review past and present attempts at modeling the general circulation, interior transport, surface layer transport and trajectories, and bottom boundary layer and sediment transport in the SAOS region.

TASK 2. Review other coastal models potentially applicable to the SAOS region.

TASK 3. Qualitatively assess the models under 1 and 2 with respect to the physics of the SAOS region.

TASK 4. Quantitatively assess the predictive capabilities of these models based upon available results and data.

TASK 5. Assess the available coastal and at-sea meteorological and sea-state data sources (both from *in situ* and remote sensors) for support of predictive modeling in order to establish limitations of predictive models, based upon these existing data sources, and to recommend additional data sources required for support of predictive modeling.

TASK 6. Assess the adequacy of existing hydrographic data to meet predictive modeling goals.

TASK 7. Assess the adequacy of models addressing the potential for damage or rupture of structures and pipelines on the continental margin under varying atmospheric, ocean wave, and current conditions.

Figure 1-1. Physical Oceanographic Model Evaluation Tasks

developed for general and interior circulations, surface trajectory, bottom sediment/boundary layer transport models, and ocean structure interaction models.

- Recommendations for the directions in which future model development should proceed in order to meet the BLM OCS program objectives.
- A time series analysis comparison of land-based and offshore meteorological data with the intent of producing a transfer function for onshore to offshore winds, thereby greatly increasing the available data base for use in surface pollutant trajectory calculations.
- Recommendations for additional meteorological, sea state, and hydrographic data monitoring in support of predictive modeling.
- Recommendations for the formatting of data products for use in modeling.
- Assessment of remote imagery for modeling applicability.

In the following section we will discuss the relationship of this program to the overall BLM Environmental Studies Program objectives, concentrating specifically on how a modeling program will help BLM to meet its goals in a more complete and timely manner. We shall then present the methodology used in this study in order to provide a framework for the material in subsequent chapters. Each one of the contract tasks has been addressed in a separate chapter of this report:

2.0 Qualitative Evaluation of Models (Tasks 1 through 3, and Task 7).
3.0 Quantitative Evaluation of Models (Task 4).
4.0 Integrated Assessment of Adequacy of Data Base (Tasks 5 and 6).
5.0 Overall Adequacy of Existing Models to Meet BLM Objectives.
6.0 Conclusions and Recommendations.

In order to provide the physical framework for the discussion of applicability of circulation models to the SAOS, we have included a thorough discussion of the geospecific aspects of that region in Appendix A.

1.1 THE ROLE OF MODELS IN THE BLM PROGRAM

The role of models in the BLM program over the past several years has been somewhat ill-defined and limited to risk analysis for the most part. In recent years, however, the need for functional, cost-effective models that yield usable products for the BLM decisionmaking process has been more widely recognized and accepted. Models play an integral role in almost every aspect of the environmental assessment process although the program does not exist merely to support modeling. In combination with other chemistry, biology, and socioeconomic studies, models become a powerful tool for more accurately predicting impact to critical resources of offshore oil and gas activities. In the following sections, the BLM model requirements are discussed in general and specifically as they apply to the South Atlantic OCS Region.

1.1.1 BLM Model Requirements in General

At the present time, the Department of the Interior, through the Bureau of Land Management (BLM), is conducting a large scale, long-term environmental studies program that is intended to gather and analyze data that can be used in making decisions related to the leasing, exploration and development of mineral resources in the submerged lands of the Outer Continental Shelf (OCS). The objectives, rationale, and approach of the OCS environmental studies program is embodied in the recently released program document entitled Study Design for Resource Management Decisions: OCS Oil and Gas Development and the Environment (1978). The objectives of the BLM OCS studies program are:

- To provide information about the environment that will enable the Department of the Interior and the Bureau of Land Management to make sound management decisions regarding the development of mineral resources on the Federal OCS.
- To acquire information which will enable BLM to assess the impact of oil and gas exploration and development on the marine environment.
- To establish a basis for prediction of impact of OCS oil and gas activities in frontier areas.

- o To acquire impact data that may result in modification of leasing stipulations and OCS orders, notices, and guidelines which provide for efficient resource recovery in conjunction with environmental protection.

Within the context of this program document, BLM has been conducting a number of studies to address the questions related to prediction of impact from activities associated with oil and gas exploration and development of the OCS. Environmental assessments, which are an essential part of the decisionmaking process, based on data and information derived from the studies program, fall into three (3) basic categories:

- o those necessary to support long-term policy type decisions;
- o those necessary to evaluate mid-term decisions associated with specific leasing decisions; and
- o those necessary to predict short-term impacts of spill incidents in a local area.

Because of the complexity of the decision making process and the interrelationships of environmental factors, the most logical way to deal with the vast amounts of available information in order to meet the requirements of the three (3) levels of assessments in a timely manner is through the use of models. Our understanding of the physical processes operating in the ocean has advanced tremendously over the past decade -- including our ability to model the processes. The types of models and their utility vary both with the nature of the physical processes themselves and the application (including time resolution) of the particular model. Because of the complexity of the processes and the nonlinearities dominated by geospecific characteristics of each OCS area, all models are limited in their utility by the available data base to supplement or complement the model and to specify realistic boundary conditions for the models. It is for the most part inadequacies in these data bases, rather than limitations in our ability to model rigorously the physical processes, that are the controlling factor in providing BLM the tools it needs to meet its objectives. It was recognition of this fact that led to the initiation by BLM of its South Atlantic OCS Physical Oceanography Field Measurements Program. As reflected by the proceedings of the BLM Modeling Workshop (April 1979), it is not felt that the data base is adequate to support the development of some of the modeling field requirements to support such model development and improvements.

As stated by BLM representatives E. D. Wood and D. Amstutz at the recent Modeling Evaluation Workshop:

> "The usefulness of modeling studies is demonstrated through increasing our understanding of processes, providing quantitative guidance for measurement programs and through provision of inputs to predictive studies. The modeling work under discussion will serve each of these purposes."
>
> "Circulation modeling is important in this area not only for the prediction of oil spill trajectories, but to determine the transport of drill muds and cuttings, petroleum hydrocarbons, and trace metals in the water column or along the bottom, especially in the proximity of sensitive biological habitants."
>
> "For tasks dealing with the surface and water column, our most pressing needs are the superior risk assessment of oil trajectories. There are similar needs for describing the transport of drilling fluids. Lastly, though by no means least important, we need to evolve a better understanding of the behavior of oil when released to the marine environment through pipeline spills. Some of the initial work addressing this topic may evolve in the discussion of bottom flow."
>
> "To the extent that our work here deals with prediction, we are concerned with events which may occur over the next twenty to thirty years. For example, consider the transport, or advection of oil spills -- this is a probabilistic problem -- the treatment of oil spills, our concerns are

with the probability of placement of real time spills. Clearly there will be couplings between these purposes which stem from this work and will be of value to those engaged in forecasting the trajectories of real time spills, e.g., USCG and NOAA."

It is the recognition of the timeliness of model developments and its own future programmatic needs for such tools for a broad range of applications that has led BLM to initiate a study for Model Application in the SAOS Region, and to plan for additional related studies in the coming fiscal years.

For the past few years, the BLM has been using, in conjunction with the U. S. Geological Survey, a stochastic model to perform risk assessments for specific lease site decisions. This model has as a primary component an oil spill trajectory model which is based on a first order Markov chain technique for the determination of the wind velocity vectors which is the principal factor in the surface oil spill trajectory analysis. The value for the velocity of the surface slick is taken as 3.5% of the "near" surface wind velocity plus a 20° deflection to the right to account for the Coriolis effect. To this is added a velocity vector for the surface currents derived from the best available information. In the case of southern California, the velocity vectors were determined from average monthly dynamic topography calculated from data collected in twenty to thirty years of cruises in the Southern California Bight. Beyond this BLM has funded, through NOAA, the development of a diagnostic model by Dr. Galt that has been applied to oil spill trajectory studies in the Gulf of Alaska and Kodiak lease areas.

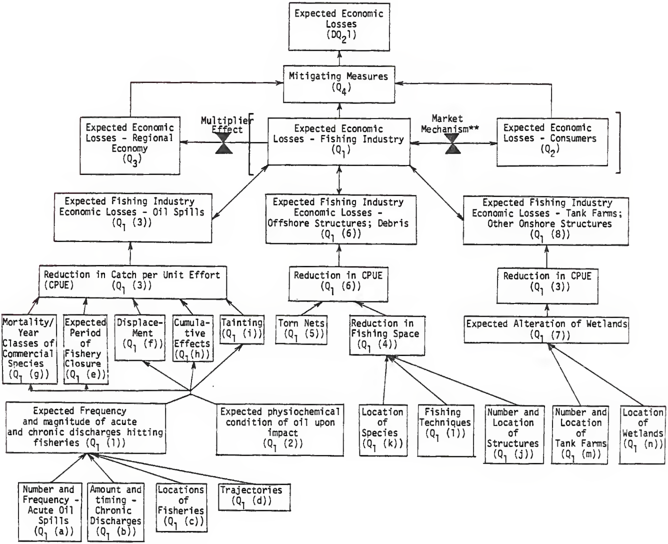
Specifically, physical oceanographic models can serve several very important functions in fulfillment of the BLM program objectives. First, they can provide more reliable values for surface current velocity vectors which would be fed into the risk analysis model now in use. Second, they can provide a better picture of the internal water column and bottom mass transport velocity vectors based on existing knowledge of the water column dynamics and available data which will permit a more complete understanding of the fate of pollutants in the marine environment introduced as a result of OCS oil and gas activities by adding a third dimension (the vertical) to the models. Finally, use of physical models in the development of field measurement schemes will greatly enhance the value and utility of the resultant data. Such an application maximizes the available human and material resources by guiding the location, number, and type of in situ or remote measurements that are made.

One expression of the actual relationship of physical models and the decision making process is shown in Figure 1-2. In this case, the issue is potential impact of pollutant discharges on commercial fishing. A key piece of information is the anticipated trajectories regardless of whether the perturbation is in the form of drilling muds, produced formation waters, or spilled oil. This information in combination with the biological and socio-economic input provides the means for determining impact on critical resources. Figure 1-3 shows the role of models specifically in the various impact assessment phases and, although it may be overemphasized in the diagram, the actual importance of physical circulation models cannot be overlooked. The best possible information on location and size of fisheries or recreation resources is virtually useless unless one is able to determine the likelihood of their being impacted by the pollutants in question. Models play a key role at three separate levels in the solution of this problem by providing:

- Accurate input of surface current vectors which are used in the risk analysis models;
- an evaluation of the importance of vertical forces in downward or upward mixing of pollutants; and
- the best estimate of the trajectory and velocity of pollutants in the ocean bottom layer.

These data can then be used in combination with information on location and nature of fisheries resources to determine possible juxtaposition of the spilled pollutants and the biological resources. Similar needs arise in the broad decision making areas of concern -- Recreation, Marine and Coastal Ecosystems, and Archaeological and Historical Resources -- four out of eight major areas of concern in the BLM OCS oil and gas decision making process. The BLM program is the first implementation of a coordinated effort involving physical measurements and model development/verification to specify circulation on the continental shelf for any such broad set of applied objectives.

COMMERCIAL FISHING*


Expected Economic Losses (DQ2 1)
Mitigating Measures (Q4)
Expected Economic Losses - Regional Economy (Q3)
Multiplier Effect
Expected Economic Losses - Fishing Industry (Q1)
Market Mechanism**
Expected Economic Losses - Consumers (Q2)
Expected Fishing Industry Economic Losses - Oil Spills (Q1 (3))
Expected Fishing Industry Economic Losses - Offshore Structures; Debris (Q1 (6))
Expected Fishing Industry Economic Losses - Tank Farms; Other Onshore Structures (Q1 (8))
Reduction in Catch per Unit Effort (CPUE) (Q1 (3))
Reduction in CPUE (Q1 (6))
Reduction in CPUE (Q1 (3))
Mortality/ Year Classes of Commercial Species (Q1 (g))
Expected Period of Fishery Closure (Q1 (e))
Displace- Ment (Q1 (f))
Cumula- tive Effects (Q1(h))
Tainting (Q1 (i))
Torn Nets (Q1 (5))
Reduction in Fishing Space (Q1 (4))
Expected Alteration of Wetlands (Q1 (7))
Expected Frequency and magnitude of acute and chronic discharges hitting fisheries (Q1 (1))
Expected physiochemical condition of oil upon impact (Q1 (2))
Location of Species (Q1 (k))
Fishing Techniques (Q1 (1))
Number and Location of Structures (Q1 (j))
Number and Location of Tank Farms (Q1 (m))
Location of Wetlands (Q1 (n))
Number and Frequency - Acute Oil Spills (Q1 (a))
Amount and timing - Chronic Discharges (Q1 (b))
Locations of Fisheries (Q1 (c))
Trajectories (Q1 (d))

---

* "Q's" refer to the set of questions found in the text of the reference.
** Economic losses will be apportioned between consumers of fish products and the fishing industry depending on the elasticity of market demand as well as possible shifts in the supply and demand functions.

Figure 1-2. Relationship between Physical Models and the DOI-BLM OCS decision-making process -- The Commercial Fishing Industry as an example (from BLM, 1978, Study Design for Resource Management Decisions).

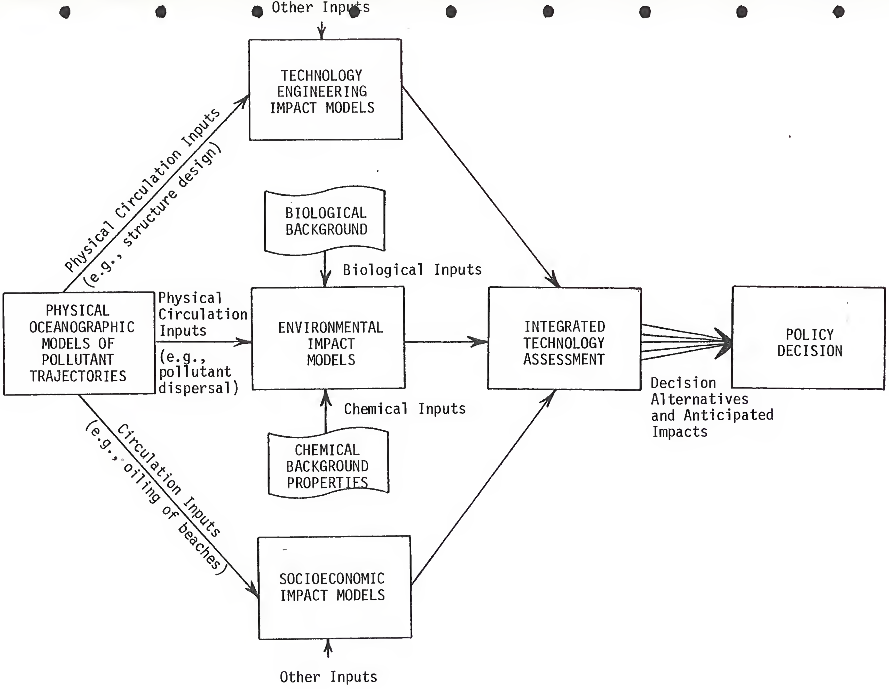

Other Inputs
TECHNOLOGY ENGINEERING IMPACT MODELS
Physical Circulation Inputs
(e.g., structure design)
BIOLOGICAL BACKGROUND
Biological Inputs
PHYSICAL OCEANOGRAPHIC MODELS OF POLLUTANT TRAJECTORIES
Physical Circulation Inputs
(e.g., pollutant dispersal)
ENVIRONMENTAL IMPACT MODELS
INTEGRATED TECHNOLOGY ASSESSMENT
POLICY DECISION
Decision Alternatives and Anticipated Impacts
Chemical Inputs
CHEMICAL BACKGROUND PROPERTIES
Circulation Inputs
(e.g., oiling of beaches)
SOCIOECONOMIC IMPACT MODELS
Other Inputs

Figure 1-3. Relationship of Physical Oceanographic Circulation Models Output and Policy Decisions

The mere collection of large amounts of oceanographic data does not ensure its timely application to problem solving unless the framework in which it is to be applied is well established and the means for applying the data are available. In the case of the BLM program, the suitable framework exists and is functional; the means for applying the data also exists in the form of models. The selection and application of the most appropriate models for the South Atlantic OCS areas has been initiated through this Models Evaluation Study by JAYCOR and reviewed by the BLM Model Evaluation Workshop, and will be furthered with the work resulting from the model application program and the out-year studies. In effect, the final link has been forged in the loop shown in Figure 1-4. For several years the BLM has been collecting benchmark and reconnaissance data along with fate and effects data; impact predictions have been made through risk analysis models which have input to the decision making process. With the exception of the diagnostic model developed by Galt for use in Alaska OCS assessments, little attention has been given to the physical oceanographic modeling aspect of the problem until now. With the unification and organization of large amounts of data into a usable data base, a potentially powerful tool for description and prediction of physical processes in the SAOS area is available.

The problems inherent in interfacing numerical and stochastic models so that they can function on a routine basis are not trivial; they are, however, surmountable. It is essential to recognize several important factors regarding their practical application:

- No one type of model can, for the foreseeable future, meet the needs of the entire BLM program in the South Atlantic;

- Without structured models derived from a data base sufficient to specify the boundary conditions and drive the models, circulation can only be interpreted by "conceptual models" of limited value in an applications sense except that such a model will permit specification of data requirements for more suitable diagnostic or quasi-prognostic models;

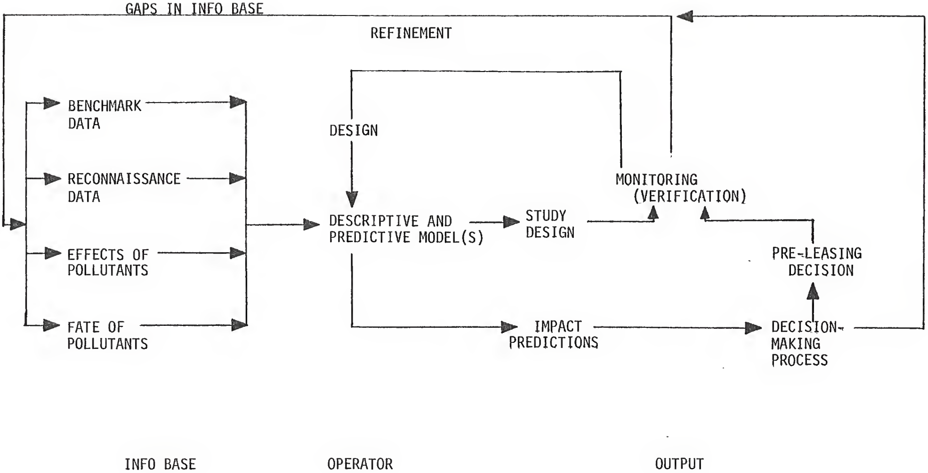


Figure 1-4. Impact Decision Mechanism

- Models must be realistic and practical, in order to address problems facing BLM now; what are needed are the best possible tools to provide the most reliable, accurate and timely results as inputs to those decisions.

By way of example of the pitfalls that might be encountered if these three factors are not given proper attention, consider the following logic: A physicist who is inexperienced in oceanography might suggest that one use: the complete Navier-Stokes equations for a rotating, stratified fluid; standard numerical techniques; parameterization, using the best available knowledge of turbulent processes, in order to close the equations at second order; the existing data base to specify boundary and initial conditions for the region; and that the answer to BLM's problem will be computed. Unfortunately, this is a prohibitively expensive approach to the problem that may not yield realistic answers at the present time, and that, given the degree of resolution required by BLM, may not be feasible even with the largest, fastest computers presently available. The appropriate equations are nonlinear partial differential equations which require knowing the velocity and mass fields at all open boundaries for all times of interest, and as demonstrated in Appendix A of this report, our understanding of the dynamics of the Gulf Stream is minimal. Few measurements of the actual current velocities have ever been made and prospects for making such continuous time series measurements are poor. Hence, the necessary boundary conditions to drive a model of this type are not available, and, therefore, the results of the model should be viewed with great skepticism.

If the ultimate model as described in the preceding paragraph were available, it would be described in the literature and highly touted by the scientific community. The BLM Workshop was unable to identify such a model even in the gray literature.

1.1.2 Specific Requirements for the SAOS Region

The South Atlantic Outer Continental Shelf (SAOS) area as defined for the purposes of this study is shown in Figure 1-5. This OCS area is unique amongst all of those of interest to BLM in that it is the only one which is influenced by

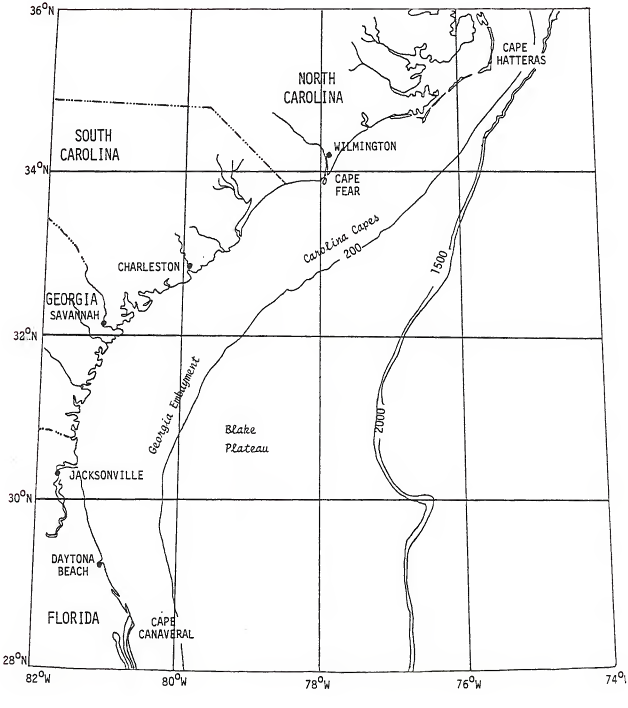


Figure 1-5. The South Atlantic Outer Continental Shelf Study Area

a Western Boundary Current -- the Gulf Stream. This imposes some unusual constraints on the types of models that can be applied in terms of the governing equations, the boundary conditions and the initial conditions. Gulf Stream Front meanders occur, warm water filaments with cold interiors are spun off, and cold core eddies are spun up along the Gulf Stream frontal cyclonic shear zone; these have a profound effect on the nutrient distribution, currents and physical processes on the continental shelf. It has been shown that due to the presence and dynamics of the Gulf Stream, there is localized upwelling on the shelf and at the shelf break which affects biological and physical shelf processes. These and other phenomena that dictate certain modeling conditions will be discussed in greater detail in Sections 2.1, 2.2, 2.3 and Appendix A of this report.

In March 1978, BLM held the first OCS lease sale in the SAOS Region, but had a relatively weak response from industry since they bid approximately $150 million on 57 of 224 tracts offered (see Figure 1-6). During the preceding two years, BLM had conducted a series of studies to obtain critical information identified by the southeastern states, the scientific community (through an open conference held in Atlanta in 1975), and the BLM itself, in order to address specific resource-use conflict questions for that sale and subsequent exploration and development activities. The issues of particular concern dealt with impact of potential pollutant discharges on sensitive coastal ecosystems, endangered species, live bottom communities and fisheries. These same issues are again the point of focus for the second SAOS lease sale (No. 56) scheduled for August 1981. Key pre-lease decisions such as tract selection, assignment of stipulations, operating orders, and notices to lessees, and comprehensive analysis of the overall environmental impact required by NEPA will also demand the same kind of output from equal or better models than were used previously. Accurate prediction of possible impact of pollutants on any of these resources depends, to a large extent, on the quality of the available data to feed models as well as the model skill itself.

In recognition of these needs, the Bureau embarked on a two-pronged program to develop adequate models and high quality data to drive the models. The model development effort was initiated through a contract with JAYCOR to examine all available physical oceanographic models and to evaluate key models that might

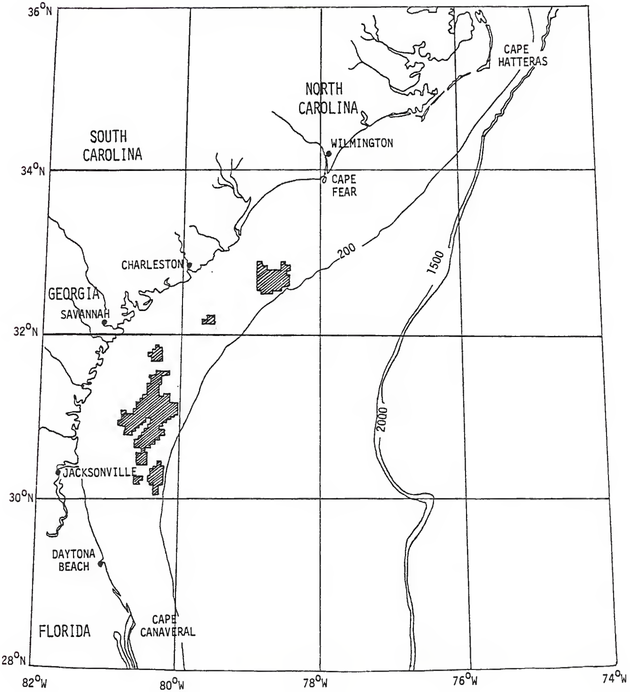


Figure 1-6. Tracts Offered for Lease in South Atlantic OCS Sale 43

be applicable to the SAOS region. The major objectives of this study were to recommend models at three levels (surface, interior water column and the bottom), to determine the sensitivity of these models to various levels of input, and to assess the quality of available data bases to parameterize and feed the models. As a part of this evaluation, a model workshop was conducted in late April, 1979, to provide up-to-date input on the status of model development and to obtain the view of experts outside the JAYCOR establishment. Highlights of that workshop suggest that:

- With regard to surface transport, advances have been made in recent years in the use of remote sensing techniques for determination of surface current vectors, and some limited data presently available suggest that additional Lagrangian drifter experiments would be useful in the model verification phase;

- with regard to internal water column processes, several highly sophisticated numerical models are available, but they would have little, if any, practical value to the BLM at this time. The working group recommended that a diagnostic model would be most applicable for BLM's problems, given any realistic monetary and time constraints. Additional field measurements would be necessary to provide boundary conditions and initial conditions for these models;

- With regard to bottom sediment and mass transport, model development is far in advance of field measurement. The critical factor in application of bottom transport models is the verification of key quantities such as shear stress and boundary layer thickness, and in bottom sediment transport models the critical shear stress for initiation of sediment transport.

It was the unanimous conclusion of the workshop participants that models could, and should, be used in the SAOS region shoreward of the Gulf Stream in the ways in which BLM intended.

Field measurements of oceanographic parameters in the SAOS Region have been ongoing for the last two to three years. Both BLM and DOE have conducted extensive field data collection efforts of everything from surface meteorological monitoring buoys, current meter moorings, Lagrangian drifter studies, hydrographic measurements, satellite and radar altimetry observations and other measurements including NDBO and USGS support activities. The major criticisms of the earlier BLM and DOE programs usually involved two questions:

- How will the existing data and the data being collected be interfaced with the risk analysis model?
- How were the sampling locations, rates of measurement, and types of measurement determined, and how do they fit the needs of the modeling tools intended to use them?

Both of these questions beg the additional question of an appropriate model set for the SAOS area. Detailed discussions of the adequacy of the existing data base and the ongoing field studies to acquire data essential for the models are presented in Section 4.0 of this report.

The Blake Plateau is a large essentially flat area between approximately 300 and 1500 meters in depth extending from approximately 77°W to 80°W and from 28°N. Very few actual measurements have been made on the Blake Plateau that are in the public domain. In the early 1960's, several oil companies joined together to do some scientific measurements on the Plateau, and in the early to mid-1970's, one of the prospective manganese nodule mining companies did some field testing of their nodule recovery systems. As a part of this testing scheme, the company conducted some field measurement of physical oceanographic parameters. These data have not, as yet, been made available to the public.

In 1976, Drs. Henry Perkins and Mark Wimbush made some measurements on the eastward margin of the Plateau and discovered that there is a strong southward flow along, and immediately over the Blake Escarpment. This was borne out in the later summary of ship drift data done by Dr. Mert Ingham of the National Marine Fisheries Service. Surface circulation over the greater part of the Plateau is predominately northward as a result of the circulation of the Gulf Stream. The interior water column and bottom transport are virtually unknown. There are scant data on the circulation over the Plateau, and only one program is actively collecting data (on the western edge of the Plateau) and that on the Gulf Stream. The BLM Modeling Workshop concluded that models of comparable skill with those possible for the shelf region could not be developed for the area seaward of the Gulf Stream (the Blake Plateau Region) on the basis of existing data; only conceptual models are considered practical for that area (see Section 5 of this report for more thorough discussion).

Since an OCS lease sale (No. 78) is scheduled for January 1984 for the Blake Plateau, the BLM is faced with a series of pre-lease decisions based on a very small data base. Many of these very early pre-lease decisions, at least those dealing with environmental matters, will depend on the best possible trajectory estimates. The only way this will be achievable for the Blake Plateau will be through implementation of a series of models; the first being a simple zero-th order model that is designed to guide future field measurements.

1.2 STUDY METHODOLOGY

A three-step process was used in the evaluation of the models and the data bases to drive the models. The first step was a semi-qualitative analysis of all available models, followed by a detailed qualitative analysis of selected models, and finally a quantitative analysis of a few of the most appropriate models. There was a coordinated evaluation of the data base and the development of a set of transfer functions for onshore and offshore winds in the study area which was designed to determine the utility of the available physical oceanographic and meterologic data in driving models. The following paragraphs describe detailed criteria used for judging the utility of the models at all three stages of evaluation and the methodology employed in compiling and evaluating the data base.

1.2.1 Evaluation Criteria

The initial qualitative evaluation consisted of compiling and reviewing more than twelve hundred separate published and unpublished references that were directly relevant to physical processes and modeling in the South Atlantic OCS area. These are all listed in Appendix B of this report, and are categorized in two different ways. In a technical sense they were divided into items that were usuable - (A) or unusable - (B) for the SAOS region indicating that for the qualitative model evaluation phase, these models were examined to determine whether or not the mathematical expressions that were used were based on sound physical assumptions and were complete, whether or not the models themselves were appropriate for the SAOS region, i.e., do the physics in the model match the physical processes in the SAOS, and whether or not the models had application to the BLM requirements for environmental assessment.

These models which were labeled "unusable" were done so on the basis of their non-utility for this study; that does not mean that they are unusable for every OCS area. Many of the models examined were precursors of later, more sophisticated models, and, although they were labeled "unusable", are, in fact, the building blocks for state-of-the-art models. Also, certain of these publications were not models, per se, but were necessary references for the background physics and related data for the evaluation. Not all of these models were examined in excruciating detail since it is fairly easy to separate rigorous from nonrigorous ones. However, all of the models listed were obtained and read. Those models labeled "usuable" were subjected to further more intensive evaluation; those that were subjected to further more intensive evaluation; those that were eliminated from further consideration were qualified with an explanation of why they were discarded. These qualifications fall into five catergories:

I. Useful as background information only;

II. Superceded by a later version of a model;

III. Analytical or quasi-analytical models;

IV. Homogeneous models; or

V. Models based on empirical/field/laboratory observations only.

Each one of the references in Appendix B has a classification immediately following the citation. All "A" designations were subjected to further detailed qualitative analysis; all "B" classifications were qualified with a Roman numeral and dropped from further consideration.

The next step in the evaluation phase was to subject each of the "A" models to detailed, more specific criteria to determine utility for meeting BLM objectives. Factors considered at this point were:

- Input requirements - type of data needed for boundary conditions, initial conditions;
- Limitations of the model either in input parameters, assumptions, or output;
- Strict applicability to the SAOS region and other coastal regions;
- Cost to run the model; and
- Error estimate of model output.

The overriding criteria at this point in the evaluation were the applicability of the model output to serve as input to the USCG risk analysis model, and the meaningfulness of the model output given the state of available field data. Probably the single most glaring conclusion of this model evaluation study is that the state-of-the-art in modeling is far in advance of the all important field data necessary for modeling validation. This is true in three out of four model categories considered (surface trajectory models somewhat lag field observations).

A final word concerning study methodology; an integral part of this evaluation was the conduct of a two-day workshop held in Research Triangle Park, North Carolina, on April 25 and 26, 1979. The purpse of this workshop was to involve leading modelers, outside the contract effort, in the review process in order to ensure inclusion of the latest possible model information, and to provide a means for testing the consistency of thinking of active modelers within, and outside of JAYCOR. Many of the workshop participants were the same scientists whose models were most critically evaluated. Input from them on improvements in the models were essential to ensuring BLM of the most up-to-date evaluation possible.

It was also an objective of the workshop to obtain the views of the participants on a broad range of issues related to hierarchical arrangement of models. The possibility and probability of interfacing surface trajectory models with water column models with bottom and sediment transport models have been widely discussed. The four-part framework established for this model evaluation workshop provided fertile ground for more definitive deliberations on this topic.

Finally, it was important to address the problem of data requirements for driving the various types of models. There has been an extensive effort on the part of JAYCOR to evaluate the spatial and temporal coverage of various types of input data, its reliability, accuracy, availability and utility. Obtaining outside views on these points in the context of BLM requirements was an essential adjunct to a discussion of models.

The desired output from the individual working groups, and ultimately from all of the participants, included:

- o Discussion of omission of significant models or new models;
- o Statements of differences with JAYCOR evaluations;
- o Suggestions for further analyses/evaluations;
- o Discussion of data coverage, adequacy and collection requirements;
- o Discussion of model sensitivity and boundary conditions; and
- o Suggestions for establishment of model hierarchies to meet BLM needs.

The format for this workshop was one that has been tried, tested and proven to be effective in meeting the stated objectives in a short period of time. The workshop agenda reflected a three-part schedule: background and summary presentations, small-group deliberations and plenary discussions. The individual working groups were kept deliberately small to encourage greater input from all participants, and the sessions were sequenced to culminate in the open discussion of individual group deliberations on the final afternoon.

It was the unanimous opinion of the twenty participants and BLM that the workshop was a success. The greatest measure of success came in the realism of the recommendations from the working groups in the context of BLM program objectives. Although highly sophisticated, state-of-the-art models of all kinds were discussed, the emphasis during group discussions was on those models which were most likely to produce meaningful results for BLM in the context of their management decision making framework. This was prehaps the most unique feature of this workshop. Workshop proceedings were prepared and delivered to BLM within a few days of the conclusion of the meeting.

2.0 QUALITATIVE EVALUATION

This section contains the results of the detailed qualitative analyses of those models selected from the list of more than 1200 background papers and models that were reviewed for applicability to the South Atlantic OCS area. All of these papers are listed in Appendix B of this report and have been given an "A" designation as a result of the initial semi-qualitative screening. The models treated herein also reflect the recommendations of the Model Evaluation Workshop conducted on April 25 and 26, 1979. At that workshop, it was pointed out that certain models had been omitted and should be considered in the final report to BLM; those models have been included in this analysis. The format for these analyses is the same for surface, interior water column, and bottom and sediment transport models; ocean-structure interaction models are treated in a slightly different manner which will be discussed below.

Each sub-section herein will be divided into two parts: a narrative of the special evaluation criteria and techniques applied to each category of models as well as a brief summary of the individual analyses and any special features that should be highlighted. The second part will be the actual analyses themselves arranged in chronological order beginning with the earliest models; this is a somewhat arbitrary selection, but is beneficial to a degree in following the sequential development of models within a given category. Each analysis is in the same format: Title, Author(s), Source, Description, Input, Numerical Procedure(s), Limitations, Example Considered (Geographic), Applicability to SAOS, Cost to Run, and Error Estimate. It is felt that these categories are inclusive and highlight the important aspects of each model necessary for identification and comparison.

2.1 SURFACE TRAJECTORY MODEL EVALUATION

Several recent review articles on oil spill trajectory modeling, and the behavior of oil on the sea surface are available as shown below.

OIL SPILL REVIEW ARTICLES

- Fallah, M.H. & Stark, R. M. (1976) Literature Review; Movement of Spilled Oil at Sea. MTS Journal, 10, 1, 3-18
- Stolzenbach, K. D., Madsen, O. S., Adams, E. E., Pollack, A. M., Cooper, C. K., (1977). A Review and Evaluation of Basic Techniques for Predicting the Behavior of Surface Oil Slicks. Ralph M. Parsons Lab. for Water Resources & Hydrodynamics, Re #222
- Rath, R. J., and Francis, B. H. (1977). Modeling Methods for Predicting Oil Spill Movement. A report to the Oceanographic Commission of Washington by the Oceanographic Institute of Washington, Seattle, Washington 99 pp.
- Wheeler, R. B. (1978). The Fate of Petroleum in the Marine Environment. Exxon Production Research Co., Special Report - 32 pp.

With the exception of a few additional models which are reviewed herein, these publications are inclusive and representative of the state-of-the-art of oil spill trajectory modeling. Additional overall review articles are not necessary at the present time. Rather, a critical assessment of the state of modeling and suggestions for improvement are required.

Eight models not covered in the previous review articles are discussed in Section 2.1.1. These include five Monte Carlo simulations, two combined numerical hydrodynamic and wind drift simulations and one addressing physical and chemical aspects other than advection. None of the previous models reviewed, nor the ones included herein, are deemed to be fully adequate to meet the BLM objectives; however, they do offer relative insight and point the way for improvement. The model presently being used by the USGS for assessing risk associated with offshore lease sales is as good as any other model presently available for that task.

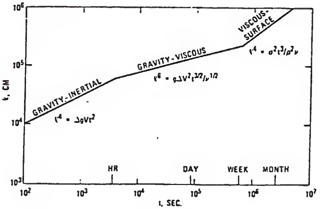
2.1.1 Special Considerations

Factors affecting oil movement and persistence on the sea surface include:

- Spreading
- Advection
- Evaporation
- Dissolution
- Emulsification
- Sedimentation
- Biodegradation and auto-oxidation (including photo-oxidation)

2.1.1.1 Spreading

Spreading occurs in response to pressure gradients, inertia, viscosity, surface tension and turbulent diffusion. The relaxation of a lens of oil on a quiescent body of water primarily occurs during the first day after the spill. Turbulent diffusion, however, will continue to be important. Spreading via pressure gradient relaxation subject to the oil viscosity, intertia and interfacial surface tension was modeled by Fay (1969) and analytically supported by Hoult (1972). The results are shown in the Figure below:



ℓ = slick size

g = gravity

V = volume

t = time

v = kinematic viscosity of water

σ = surface tension

ρ = density

Figure 2-1 The size ℓ of an oil slick as a function of time t for a 9.08×10^6 kilogram spill. (from Fay, 1969).

Three different regimes are defined depending upon the principal pair of forces involved. Initially the pressure gradient and inertial terms dominate. Viscous forces then supercede the inertia terms and finally, the pressure gradient gives way to surface tension. Spreading ceases in this formulation when the sign of the surface tension reverses or the oil no longer "wets" the sea surface.

Turbulent diffusion, neglected in the Fay-Hoult formulation was found to be very important in the field observations of Murray (1972). A comparison between the observed slick behavior, that predicted by the Fay-Hoult formulation, and that modeled via turbulent diffusion is shown on Figure 2-2 (taken from Murray, 1972).

This figure demonstrates the difficulty in modeling oil slick spreading. The deterministic approach of Fay and Hoult appears to be inadequate for field applications.

Something that this figure does not show, but which is a very important consideration in the fate of spilled oil, is the differential spreading of oil. Crude oil spreading is a function of the physicochemical characteristics of the oil as well as the environment in which it is spilled. Few, if any, oil spills behave in an ideal fashion and spread into a monomolecular layer over the surface of the ocean. It is much more common for the oil to break into pancakes or windrows after initial gravity spreading has diminished, and to have a sheen form between the pancakes (see Figure 2-3). There is a substantial body of research information, going back to Langmuir's work in 1933, which deals with the theoretical and experimental aspects of spreading of spilled hydrocarbons. However, there are no models, to date, which accommodate non-uniform spreading and the effects of such spreading on biodegradation and physicochemical alteration of the spilled oil. The most comprehensive treatment of this topic to data has been that done in connection with the ARGO MERCHANT spill.

2.1.1.2 Advection

The aspect of oil spills that has been most frequently modeled is horizontal advection. The initial concern was, of course, where the oil would go if

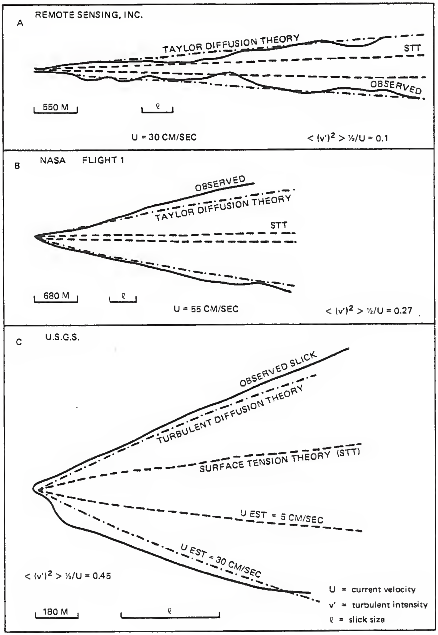


Figure 2-2. The comparison between observed slicks and slick outline predicted by the Taylor diffusion theory and surface tension theory of Fay (1969). In A and B the current speed was observed onsite. In C the current speed is estimated at the average value for the incident (29 cm/second) for the turbulence theory and estimated at 5 cm/second for the surface tension theory to maximize possible agreement between Fay's theory and the observation. This figure is from Murray (1972).

it spilled at point A and how quickly it would get there. The earliest oil spill models were the type were an "ellipse", which simulated the shape of a patch of spilled oil, was moved along the surface of the water by means of a random walk process. There were no attempts to account for spreading or weathering of the spilled oil, and the size of the patch was directly proportional to the amount of oil released in the hypothetical spill. Additional parameters have been added to these models, although very slowly, to account for spreading, but no one has been able to deal successfully with the vertical advection problem. The modeling of oil slick advection has generally followed the equation:

$$\frac{d\vec{x}}{dt} = \vec{V}_c + \vec{V}_w + \vec{V}_T$$

where x is the position vector of the slick which changes in response to the vector addition of V_c, the mean current or circulation, V_w, the wind induced drift, and V_T, the tidal current. Tidal excursions are generally on the order of 1-2 km and tend to further spread the slick rather than causing significant net advection. Consequently, some models, such as the USGS one, neglect it.

The wind drift is generally modeled using a wind speed and a deflection angle of some 20° to the right of the wind direction. The 3% rule (some form of which is most frequently used in wind drift oil spill models) has an empirical basis and crudely follows theoretically from continuity of stress across the air-sea interface. Letting the stress be proportional to density times a friction speed squared, it follows that

$$V_w = (\rho_a/\rho_w)^{\frac{1}{2}} V_a \approx 0.03V_a$$

where V_w (V_a) is the water (air) speed and $\rho_w(\rho_a)$ is water (air) density. A recent paper by Lange and Hufnerfuss (1978) discusses a laboratory wind tunnel experiment addressing the effect of steady winds and/or waves upon the drift of a monomolecular slick. The slick drift in response to deep water waves was in close agreement with the theoretical Stokes drift:

$$U_s = a^2k^2c$$

where U_s is the Stokes drift, and a, k, and c are the wave amplitude, wave-number and phase speed. The slick drift in response to wind alone was found to be in agreement with previous studies as summarized in Table 2-1.

The drift speed or the wind factor appears to be in the range of 2.6% - 5.8% including both the effects of wind and waves. The partition between pure wind drift and wave-induced transport remains in question.

Huang (1979) discusses a new approach for estimating surface drift based upon the Eulerian mean wave momentum. His model suggests an approximate 3% of the wind speed drift magnitude in the direction of the wind velocity. Its utility lies in the fact that such drift depends upon the average significant wave slope which can be measured rather than upon wind velocity or stress. The model can also be expanded to give the velocity distribution and effective eddy viscosity for the mixed layer. At the present time, the model remains untested and somewhat controversial. Testing the hypothesis will require field studies considering both sea state and drift.

The final term in the advection equation V_c is usually obtained from whatever data source is available. These have included drift bottles, geostrophic current calculations, and in a few cases current values derived from hydrodynamical models. Such an approach has been used by Galt and Pease (1977) wherein a diagnostic model of the circulation of the Gulf of Alaska was developed and an attempt was made to describe the movement of spilled oil under various scenarios. This approach had some serious flaws due to basic weaknesses in the model rather than in the appropriateness of the technique. The results of our evaluation (see Section 2.1.1) show that it is possible to use a diagnostic model to more accurately calculate current vectors, but that the model would have to be relatively simple so that the results could be verified through field measurements. There are a number of highly sophisticated three-dimensional, time-dependent numerical models available (e.g., Blumberg and Mellor, 1977) which describe circulation on the continental shelf; however, the results are virtually impossible to verify because of the degree of detail of the model output and the lack of appropriate field data.

	Type of Study	Method of drift determination	Wind speed range (m s^{-1})	Drift speed / wind speed (%)
Lange & Hufnerfuss (1978)	laboratory	monolayer-oleyl alcohol	2.4-8.5	3.0-4.8
Wright and Keller (1971)	laboratory	0.64 cm^2 2 mil polyethylene spheres, disks, 0.32-1.27 cm diam		
Wu (1968)	laboratory	spheres, 0.08-1.0 cm disks 0.25 cm diam, 0.06 cm thick	3.5-13.4	2.8-4.8
Plate et al (1969)	laboratory	disks, 0.6 cm diam, wax paper	3.6-12.8	3.2
Mizuno and Mitsuyasu (1973)	laboratory	disks, 0.6 cm diam, paper	2.5-10.0	3.0-3.4
Dobroklonskiy and Lesnikov (1972)	laboratory	spheres, 0.04-0.3 cm diam, polystyrene	7.0-12.0	2.6-3.1
Keulegan (1951)	laboratory	paraffin flakes	3.0-12.0	3.3
O'Brien (1971)	laboratory	crude oil, fuel slicks	5.0-10.0	2.8-3.2
Shemdin (1972)	laboratory	disks, 0.6 cm diam. paper	3.1-9.1	2.6-2.9
Van Dorn (1953)	artificial pond	disks 2.54 cm diam, 0.13 cm thick, cork	3.0-13.0	3.0-4.3
McArthur (1962)	lake	monolayer-cetyl alcohol	2.7-7.0	4.8-5.8
Smith (1968)	open ocean	crude oil slick	unknown	2.6-4.7
Brockis (1968)	open ocean	crude oil slick	unknown	4.0
Tomczak (1964)	open ocean	crude oil slick	unknown	4.3
Tomczak (1964)	open ocean	plastic cards	up to 15.0	4.2
Hughes (1956)	open ocean	plastic cards	0.4-14.0	3.3

Table 2-1 Comparisons of Laboratory and Field Studies on Wind Induced Surface Drift (From Lange and Hufnerfuss, 1978)

As an example of an application of the preceding advection model, three figures (2-4 through 2-6) showing the South Atlantic Outer Continental Shelf lease area have been taken from the USGS risk analysis model for OCS Sale 43 (Slack and Smith, 1976). Several coastal sites appear to be vulnerable to oil spill damage which emphasizes the importance of accurate slick behavior modeling for this region and others.

2.1.1.3 Evaporation

Evaporation is, along with dissolution, one of the most immediate processes acting on spilled oil. It can account for more than 50% loss by volume and will be almost complete within 96 hours of the spill. Evaporation is a function of wind speed, sea state, temperature (of the water, the air and the crude), solar radiation, composition of the crude (primarily the vapor pressure and diffusion properties of the oil which is a reflection of the composition) and the dimensions of the spill.

Almost all n-paraffin compounds with boiling points up to 270° to 280° C evaporate within the first few days of a spill - these are the n-alkanes less than C_{16} leaving behind a residue rich in aromatics and higher molecular weight alkanes. Over the next 100 days the rate of evaporation is extremely slow and will generally only involve those compounds with boiling points up through 350° to 360°.

There have been two models for predicting evaporation rates from crude oil that have shown some promise: Fallah and Stark (1976) and Mackay and Matsugu (1973). The Fallah and Stark model is for a mixed hydrocarbon assemblage and is stated as:

$$\frac{dV}{dt} = KA^{\beta}\, u(Z)\alpha\, (P_s - P_a)$$

where A is the liquid surface area; $u(Z)$ is the wind speed at height Z above the liquid surface; P_s is the saturation vapor pressure at the liquid surface temperature; P_a is the partial vapor pressure in the air upwind of the liquid surface; K, α, and β are constants; V is volume; and t is time. The primary problems with

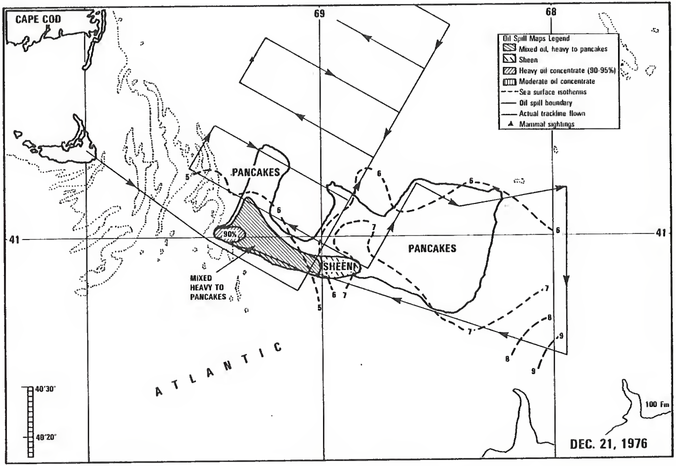


Figure 2-3. Example of Irregular Spreading of Spilled Oil (taken from NOAA Special Report entitled "The ARGO MERCHANT Oil Spill," March, 1977)

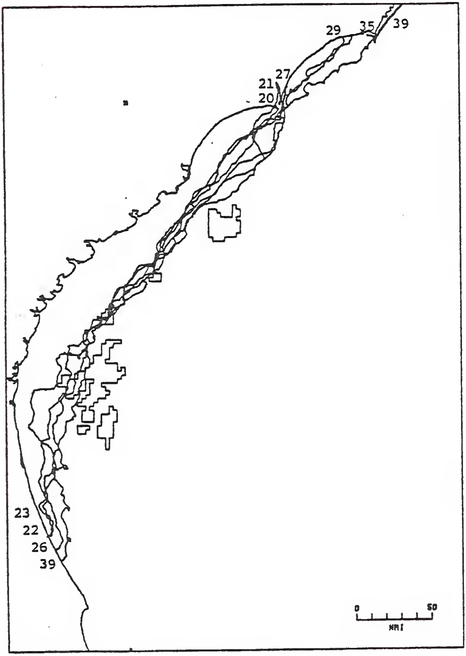


Figure 2-4. Example oilspill trajectory results for a spill site near the center of the proposed lease area: summer conditions. Number on trajectory reaching the coast gives time to land in days.

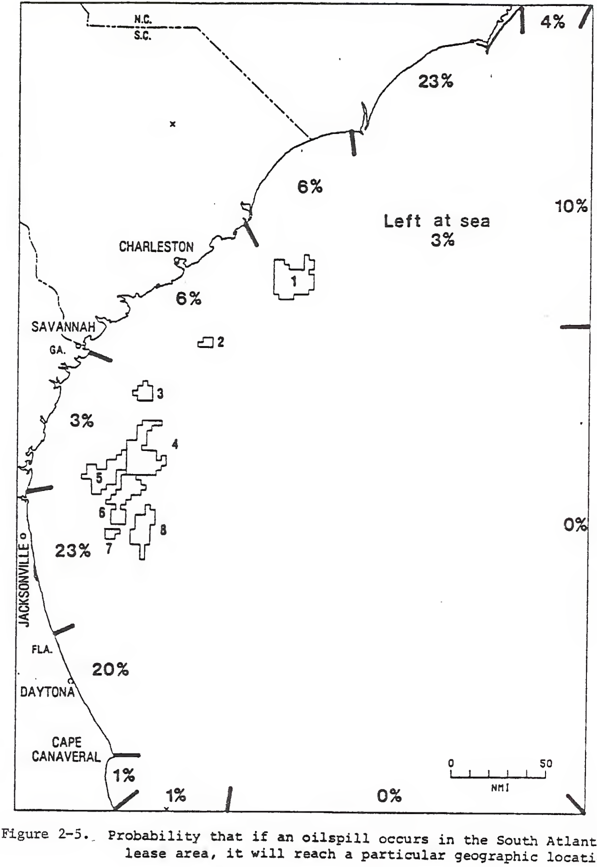


Figure 2-5. Probability that if an oilspill occurs in the South Atlantic lease area, it will reach a particular geographic location.

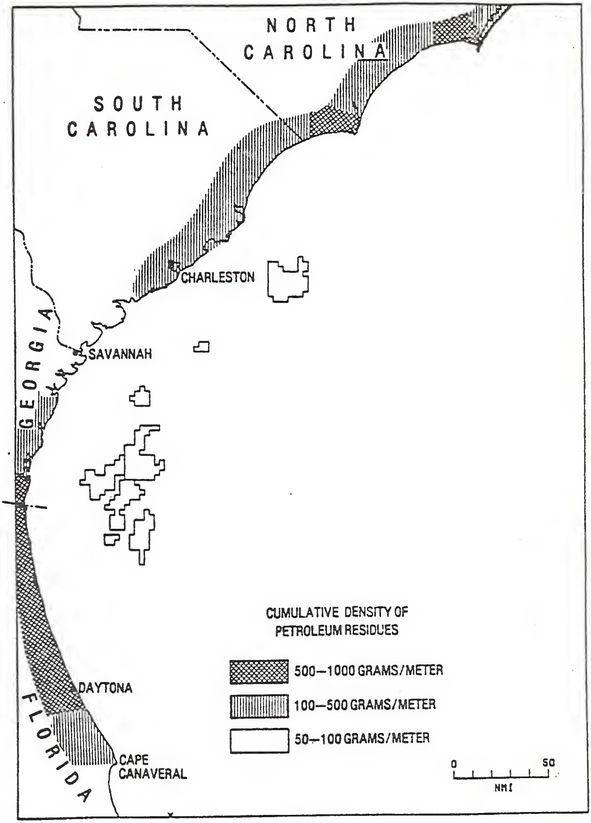


Figure 2-6. Projected cumulative distribution of petroleum residues on South Atlantic beaches resulting from small scale, chronic spillage during the production life of the lease area. Estimated densities do not include existing background levels resulting from tanker washings and natural seeps.

this relationship are that: the constants vary according to temperature differences between the air, water and oil. Although initially P_a can be set equal to zero, the $P_s - P_a$ relationship changes with time (very rapidly in the first day or so following the spill), and there is no accounting for the physical variability in the crude oil itself. Use of this model would require rather extensive laboratory determinations of the vapor pressures of various types of crude and the changes in those vapor pressures as weathering proceeds.

Another model by Mackay and Matsugu (1973) has some promise because of its accuracy and simplicity. It is, however, for predicting the evaporation rates of pure compounds from a liquid-gaseous interface and therefore has limited utility to crude oils because they are multi-component liquids. It can be used for very short periods of time in describing such evaporation, but because of the effect of partial vapor pressure from other components, the expressions are applicable on a limited basis. The flux in moles m^{-2} sec $^{-1}$, ϕ_e , of a single component hydrocarbon leaving the surface of a slick is given by:

$$\phi_e = K_m \frac{(P - P_\infty)}{RT}$$

The driving force is the difference in the vapor pressure $(P-P_\infty)$ of the liquid on the upper surface of the slick (P) and the atmosphere (P_∞) which in most cases will be zero. K_m is a rate constant which is a function of the transport properties of the atmosphere above the spill (which is dependent upon wind velocity, spill area and sea surface roughness), and transport properties of the liquid, R is the gas constant for the compound of interest; and T is the temperature of the liquid.

A factor which must be taken into account in developing a suitable model of evaporation from the surface of a spill is the irregular spreading discussed in the foregoing section. It was emphasized there that spreading is not a uniform process and the formation of pancakes, windrows and slicks will significantly influence the rate of evaporation. The evidence of the influence of "crusts" or "skins" on evaporation from weathered oil is inconclusive at this time, but must be taken into account.

2.1.1.4 Dissolution

Hydrocarbons in the dissolved state are more lethal to every form of marine life into which they come in contact than hydrocarbons in any other form. Fortunately, hydrocarbons are relatively insoluble in sea water so that only about 5 percent by weight of spilled crude is dissipated through dissolution. This is, of course, a function of composition of the crude, temperature, salinity, wind stress on the surface of the spill, spill area and turbulence. In terms of relative importance in the weathering process, dissolution plays a minor role and is active for only a matter of hours after the spill. Generally speaking, within a homologous series, solubility increases with molecular weight; also, the solubility of compounds is inversely proportional to the degree of unsaturated bonding (acetylenes > diolefins > olefins > parafins) and ring closure (McAuliffe, 1966). Aromatics are very toxic, and are one or two orders of magnitude more soluble than their straight chain counterparts.

Up to the present time, there have been limited attempts to make field measurements of dissolved hydrocarbons under slicks. Mackay and his colleagues will in the near future be attempting to make measurements of both dissolved and particulate hydrocarbons under fresh spills in the marine environment. From these he hopes to be able to develop valid models for both dissolution and emulsification. McAuliffe (1976) has made measurements of concentrations of dissolved hydrocarbons beneath slicks under laboratory conditions and found that the maximum concentrations occurred within thirty minutes of the spill.

2.1.1.5 Emulsification

The process of emulsification of spilled oil could result in dispersion where water is the continuous medium and oil droplets are suspended, or formation of a "mousse" where oil is the continuous medium, and droplets of water are suspended. In either case, the effective volume of the spilled oil is increased by as much as 4 to 5 fold making containment and cleanup more difficult. Emulsification is primarily a function of turbulence and composition of the crude, although temperature was shown to play some role in mousse formation following the ARGO MERCHANT spill. The critical factor in determining whether a water-in-oil or oil-in-water emulsion is formed is the amount of natural surfactants available in the spilled crude. These surfactants are primarily asphaltenes, that is, the fraction of a crude oil which is not extractable in n-pentane and is highly hydrophilic relative to other hydrocarbons. Other compounds such as organic acids, aldehydes, and certain sulfonates are also hydrophilic and their presence in crudes will increase the likelihood of emulsification. In general, in the presence of more than 2% asphaltenes or 5% resins, mousse formation or perhaps even dispersion is to be considered highly likely (Strassner, 1968).

One important difference between mousse and dispersed oil is in the subsequent rate of degradation. Processes are slowed because the effective volume of the oil is increased and less oil is exposed to photo-oxidation, and the suspended water droplets do not contain sufficient oxygen or nutrients to sustain biodegradation or auto-oxidation. In dispersion, there is actually an increase in the amount of oil surface area exposed to water which has a source of oxygen and nutrients. Therefore, biodegradation and auto-oxidation are actually enhanced. In either case, the possibility of sedimentation is more likely because of the increased amount of detrital mineral, and non-petroleum organic matter that is incorporated in the emulsion, thereby increasing the specific gravity of the oil and the likelihood of sinking.

2.1.1.6 Sedimentation

In the classical sense, sedimentation involves the sinking of particulate matter through a fluid medium, the material obviously having a specific gravity greater than that of the fluid medium (fresh water = 1.0, salt water = 1.032 on the average). Crude oils have specific gravities ranging from 0.62 at the lightest end to 0.96 at the heaviest end. Their effective specific gravity can be increased by several mechanisms: evaporation and dissolution, or adsorption or absorption onto particles more dense than sea water. In any case, the oil particles become heavier than the sea water and sink to the bottom.

Most of the evidence gathered so far on sedimentation of oil has been experimental and has been inconclusive although the amount of related literature on surface activity of mineral particles and organic particles in sea water is voluminous.

- Mineral particles tend to aggregate around oil globules until the flocs begin to sink.

- Clay particles, which have the highest surface to weight ratios of common mineral grains in sea water, tend to adhere to oil more readily than other minerals. This may also be due to the extremely high surface charges associated with clay minerals.

- Sedimentation of oil is directly proportional to salinity.

- The presence of organic material tends to interfere with absorption (Meyers and Quinn, 1973).

The important point of sedimentation is that the ultimate fate of spilled crude oils left in the environment is sinking and subsequent slow biodegradation. Very little has been done to improve our understanding of the crude oil sedimentation problem and yet it is one of the most crucial links in the fate of petroleum problem. Slightly more is known about the residence time of sedimented hydrocarbons in the bottom sediment layer, and recent research by Kaplan and his associates at UCLA and Farrington and Teal at Woods Hole Oceanographic Institution should shed some light on rates of degradation of petroleum in sediments, the factors influencing such rates and the types and amounts of products that can be anticipated.

2.1.1.7 Auto-Oxidation

The term auto-oxidation as we use it here will include photo-oxidation and bio-oxidation, as well as normal chemical oxidation. All of these processes occur over the longer term and involve the degradation of spilled crude oil by means of reaction with oxygen molecules and/or the removal of hydrogen atoms from organic compounds. The specific processes have been very well summarized by Wheeler (1978) and it is not particularly useful to reiterate them here. However, it is important to expand on a brief comment in Wheeler's conclusions (See #5, Page 21). In those conclusions, he states that "Some suggest that this alteration may yield potentially toxic or carcinogenic intermediate or final products". Although the magnitude of this particular problem is not known, it has been shown by

Patel, et al (1978), that highly carcinogenic arene oxides are formed when crude oil slicks are exposed to a normal range of sunlight under controlled laboratory conditions. In recently completed follow-up studies, Laseter (personal communication) has derived the first rate curves for photo-oxidation of phenanthrene which he is proposing as a model for higher molecular weight polynuclear aromatic hydrocarbons which have been shown to have a long residence time in the environment and which are known carcinogens.

2.1.1.8 Biodegradation

The volume of literature on biodegradation of crude oil in the marine environment is staggering, and the number of workshops, symposia, and special sessions of annual meetings that are devoted to this topic is growing. The basic biodegradative processes of concern for spilled crude are ingestion and metabolism by both macroorganisms and microorganisms, although the latter far outweigh the former in importance in this process. The most comprehensive and recent summary of our state of knowledge of microbial degradation of oil is in Zobell (1979).

Biodegradation of spilled crude is a process which begins to be prominent on the order of days after a spill, and may continue to be important for months after a spill. This process is primarily a function of temperature, composition of the crude, the nature of the ambient bacterial populations, microbial predators, available nutrients and oxygen. There are more than 200 species of bacteria, yeast, and filamentous fungi which have been shown to metabolize one or more hydrocarbons ranging from methane up through C_{40} compounds (Zobell, 1973). The n-alkanes are most readily oxidized, followed by the iso-alkanes, olefins and aromatics. Certain types of wild mixed-culture bacteria do, however, degrade aromatics more rapidly than n-alkanes; this seems to be related to the degree of exposure of the bacteria to aromatics in the natural state. The mechanisms for degradation of these various compounds is well studied as are the nature of the intermediate products and the range of conditions under which the transformation take place. There is also an abundance of literature on the distribution and characteristics of hydrocarbonoclastic microorganisms in the environment. However, until recently, there has been little done on the reaction rates and intermediate metabolic products (Zobell, 1973) which are essential to developing a working model of microbial degradation.

Microbes that are capable of oxidizing petroleum occur in some amount in just about every area of the marine environment that has been sampled. They are much more abundant in highly polluted areas and in areas where there is a fresh and continuous source of hydrocarbons. The assemblage of microbes found at any given site seems to be more closely related to the mix of hydrocarbons available than to physical factors. Zobell (1966), has done a number of analyses on samples from Barataria Bay, Louisiana where large amounts of natural hydrocarbons are found and has recorded up to 10^9 oil oxidizers per ml of bottom sample. Research sponsored by the Bureau of Land Management on distribution of hydrocarbonoclasts in open ocean environments yielded populations that were several orders of magnitude less than in polluted areas (Passman, 1979).

Microorganisms generally metabolize a very narrow range of hydrocarbons and most frequently there are in a homologous series because the enzymes which act on the hydrocarbons are very specific. For this reason the use of mixed cultures of microorganisms to seed spilled oil, and thereby hasten degradation, has been investigated on a fairly wide basis. Recent studies have been conducted by Ahearn (personal communication) on the rate of degradation of a mixed hydrocarbon substrate. In these experiments he used a mixture of nine pure compounds - including aromatics commonly found in crude oils - and measured the rates of oxidation and co-oxidation of the compounds. These are the first such rate measurements known to have been made on mixed petroleum substrates, and will aid immeasurably in the development of a suitable biodegradation modeling algorithm that could be used in an integrated oil spill fate model.

2.1.1.9 Summary of Special Considerations

The multitude of factors affecting oil spills greatly complicates the modeling effort. All of the factors have been treated to varying extent in the aforementioned review articles. However, additional research is required in all areas.

Several of the oil spill trajectory models, for example, the USGS model used for risk analysis related to the Department of the Interior offshore lease sales, neglect all influences except for advection. Though incomplete, they are reasonable approaches from an engineering viewpoint. Since evaporation, dissolution, emulsification, sedimentation, biodegradation, and auto-oxidation are non-conservative, they tend to dissipate the spill. By not including them, a safety factor of two or more (depending upon travel time to landfall) is automatically built into the models.

In the following section, eight models will be discussed in greater detail:

1. Mackay D. and Leinonen, P. J. (1977), Mathematical Model of the Behavior of Oil Spills in Water With Natural and Chemcial Dispersion.
2. Premack, J., and Brown, G. A. (1973), Prediction of Oil Slick Motions in Narragansett Bay.
3. Galt, J. A. & Pease, C. H. (1978), The Use of a Diagnostic Circulation Model for Oil Trajectory Analysis.
4. Tayfun, M. A. & Wang, H. (1973), Monte Carlo Simulation of Oil Slick Movements.
5. Fallah, M. H. & Stark, R. M. (1976), Random Drift of an Idealized Oil Patch.
6. Dietzel, G. F. L., Glass, A. W., Van Kleef, P. J., & Van Den Beukel, C. H. (1976), SLIKTRAK.
7. Det Norske Veritas (1977), OIL SIM
8. Slack, J. R. & Smith, R. A. (1976), An Oilspill Risk Analysis for the South Atlantic Outer Continental Shelf Lease Area.

The first model, which does not include advection, offers a comprehensive treatment of the non-conservative aspects of oil slick dissipation. It has not been included in other review articles.

The second and third utilize hydrodynamical numerical models to treat slick advection by currents. This approach has the potential of greatly improving trajectory simulation.

The remaining models are probabilistic. Tayfun & Wang (1973) was one of the original attempts at using random walk and time series techniques. The time series approach has subsequently been neglected and the more recent probabilistic models have used first order Markov transition matrices.

2.1.2 Detailed Qualitative Evaluation of Selected Surface Trajectory Models

2.1.2.1 Title: Mathematical Model of the Behavior of Oil Spills on Water with Natural and Chemical Dispersion.

Authors: Mackay D. And P. J. Leinonen.

Source: Fisheries and Environment Canada, Environment Protection Service, Economic & Technical Review Reports #EPS-S-EC-77-19.

Description: The model provides a computer simulation of oil slick size and properties as a function of initial composition, sea state, wind speed, temperature and artificial dispersion. It is mainly a diagnostic model and the report provides valuable insight to the many chemical and physical aspects of oil spills. The model does not include advection. It considers evaporation, vertical diffusion, dissolution, emulsification, spreading and horizontal eddy diffusion. It addresses the exposure of marine biota to the hydrocarbons associated with a spill.

Inputs: The inputs include the initial oil composition, sea state, wind speed, temperature and various rate constants.

Procedures: The various processes stated above are all modeled using differential equations and rate constants applicable to each of them.

Limitations: As a diagnostic model of the chemical behavior of oil on water, the results have considerable utility. The model does not address trajectories since it excludes advection.

Examples Considered: 34 spills under varying conditions.

Applicability to SAOS Region: The chemical aspects are applicable to the SAOS region.

Cost: Unspecified.

Error Estimate: Unspecified

2.1.2.2 Title: Prediction of Oil Slick Motions in Narragansett Bay.

Authors: Premack J. and Brown, G. A.

Source: Proceedings Joint Conference on Prevention and Control of Oil Spills, Washington, DC, March, 1973

Description: The authors simulated (hindcasted) the behavior of an oil spill in Narragansett Bay, RI. Wind drift was modeled using a wind factor and deflection angle applied to real time winds. Currents were calculated using a separate hydrodynamic model of Narragansett Bay. Spreading was modeled using gravity, viscosity, surface tension theory. The model is site specific, but it is one of the few examples where hydrodynamical models were used in conjunction with surface wind drift to arrive at a slick trajectory.

Inputs: The inputs include the spill location, rate and duration, real time winds and a hydrodynamic model for current.

Procedures: Oil spreading and slick advection are considered. Wind drift and current (tidal) are additive.

Limitations: The model is site specific. It requires empirical data (which may also be site specific) for the wind factor and deflection angle. It requires an accurate hydrodynamical model. Though the latter is a limitation, the concept of using a hydrodynamical model to calculate current, rather than drift bottles, etc., should certainly provide improvement to trajectory models.

Example Considered: The P. W. THIRTLE Spill in Narragansett Bay.

Applicability to SAOS Region: Inapplicable in the present form, but conceptually feasible.

Cost: Unspecified.

Error Estimate: Indeterminate for other applications; however the model hindcasted the Narragansett Bay spill very well.

2.1.2.3 Title: The Use of a Diagnostic Circulation Model for Oil Trajectory Analysis

Authors: Galt, J. A. and Pease, C. H.

Source: EPA/API/USCG Oil Spill Conference, New Orleans, March 1977, and "Numerical Studies - PMEL", Report to OCSEAP, September 1978, Chapter 6.

Description: A diagnostic circulation model is coupled with a surface drift alogrithm to simulate oil slick trajectories. The diagnostic circulation model consists of a linear superposition of barotropic wind-driven and baroclinic density-driven circulations. The baroclinic portion has temporally constant spatial distribution dependent upon the input density field; the barotropic portion changes instantaneously in response to selected synoptic weather patterns. Together they comprise the water circulation. The wind drift is added to the water circulation using a 3 percent wind factor.

Inputs: The model requires a density field for driving the baroclinic portion of the model, and a wind field derived from synoptic sea surface pressure charts and coastal and at-sea meteorological stations.

Procedures: The three aspects of the surface velocity: 1) baroclinic density-driven, 2) barotropic wind-driven, and 3) wind drift, are calculated separately and added to give a trajectory.

Limitations: Spreading and chemical effects (evaporation, weathering, etc) are not included. Uncertainties exist in the circulation modeling and a hydrographic data base is required for different seasons. The circulation model is linear, therefore, its region applicability may be limited. The 3 percent wind factor with no deflection angle is subject to a factor of 2 or so error.

Example Considered: The northeast Gulf of Alaska.

Applicability to the SAOS Region: The model could be adapted; however, the non-linearities associated with the Gulf Stream may cause difficulties.

Cost to Run: Unspecified but probably considerable since the generation of the meteorology and other data fields would be manpower intensive.

Error Estimate: Unspecified. The use of a hydrodynamical model should be a vast improvement in estimating the water circulation. The wind drift, however is subject to similar errors as the other models considered.

2.1.2.4 Title: Monte Carlo Simulation of Oil Slick Movement

Authors: Tayfun, M. A. and Wang, H.

Source: ASCE Journal, Waterways, Harbors, Coastal Engineering Division, August 1973

Description: A computer model is presented to simulate the movement of an oil slick by winds and tidal currents. A Monte Carlo approach is taken using two separate stochastic tools to generate winds: 1) a random walk in which the winds have no memory, and 2) an autoregressive time series model in which the wind memory is developed from its autocorrelation structure. Simulations were performed by letting a large number of particles drift at 3 percent of the wind speed at a cum sole deflection angle arrived at via Ekman theory, plus 56 percent of the tidal current velocity determined from published charts.

Inputs: Wind time series for the generation of 1) probability distributions for speed and direction in the case of the random walk or 2) the autoregression coefficient for the case of the time series model.

Procedures: A large number of point masses are allowed to drift on a 3 x 3 nautical mile grid at a 2 hour time interval. The distribution of particles after a given interval of time determines the probability that a slick would reach a certain point.

Limitations: The model does not include spreading or chemical factors, i.e., evaporation, weathering, etc. It is strictly an advection model. The uncertainty in the wind factor and deflection angle may be as large as a factor of two; the 56 percent factor applied to tidal current velocity is arbitrary and physically unfounded; and the use of a tidal current chart alone is insufficient to account for the circulation.

Example Considered: The region off Cape Henlopen, Delaware at the mouth of Delaware Bay.

Applicability to the SAOS region: The model is applicable after deriving new wind statistics.

Cost to Run: Unspecified

Error Estimate: Upwards to 100 percent depending upon currents and wind drift.

2.1.2.5 Title: Random Drift of an Idealized Oil Patch

Authors: Fallah, M. H. and Stark, R. M.

Source: Ocean Engineering, 3, 1976

Description: A probabilistic model is developed for describing the center of mass of an oil slick under the combined effects of wind drift and currents. A 3 percent wind factor and an Ekman theory deflection angle are used for the wind drift, and a 56 percent factor is used for the current advection. The probabilistic description is derived in the form of characteristic functions for winds with no memory. A transitional effect which allows the slick to curve onto a new path is added to model the inertia of the fluid, (see comments under limitations) thereby allowing the water column to remember the prior time step velocity. The characteristic functions are determined analytically; however, they require probability distribution for the random variables considered, i.e., wind speed and direction. Given these probability distributions, slick statistics can be generated.

Input: Wind speed and direction data for generating probability distribution functions.

Procedures: Characteristic functions are computed from which the oil slick statistics, i.e. means and variances can be calculated.

Limitations: The 3 percent wind factor and Ekman theory deflection may be subject to factor of 2 variations; the 56 percent current factor lacks a physical basis; and the model does not include spreading or chemical effects (evaporation, weathering, etc.). The statistical approach in modeling the winds does not include memory. This is an unnecessary limitation since synoptic weather systems generally have time scales of several days. Memory is arbitrarily modeled into the transition from one wind direction to another, but the transition factor is obscure and the physical basis for this is somewhat arbitrary.

Example Considered: A sample calculation is offered.

Applicability to the SAOS region: The model could be applied.

Cost to run: Unspecified

Error Estimate: Upwards to 100 percent depending upon wind drift and current information.

2.1.2.6 Title: SLIKTRAK

Authors: Dietzel, G. G. L., Glass, A. W., Van Kleef, P. J., and Van Den Beukel, C. H.

Source: Progress report, Shell Internationale Petroleum Maatschappy B. V., The Hague Exploration and Production, April 1976.

Description: SLIKTRAK is a computer program intended to simulate the drift of daily oil lots on the sea surface until they impinge upon a coast, and to estimate the total costs of the spill, the cleanup operations and the pollution consequences. The simulation includes advection by wind drift and a mean current, evaporation, cleanup efficiency based upon sea state and dispersion. The descriptive portions of the progress report are very brief, and it is unclear how each of these factors are treated.

Input: A mean current vector for each grid sector; a historical wind and sea state data base; and spill location, flow rate, and duration.

Procedures: A daily wind velocity record generated (in a specific manner) is randomly entered and a daily drift velocity is computed using an unspecified drift factor. This drift vector is added to a constant drift vector supplied from an unspecified source. The slick volume after the third day is reduced from the first day volume by evaporation, cleanup efficiency, and chemical dispersion. Evaporation is unimportant at future times. The volume of oil reaching the coast is recorded and the total costs are estimated. The simulations are repeated to give probability distributions for: 1) oil cleaned by primary and secondary combat, 2) oil reaching the coast, 3) oil passing out to the ocean, and 4) total costs.

Limitations: The wind record may not be indicative of the true at-sea winds. The wind factor magnitude and direction may be in error by factors of 2 or more. The use of a constant residual current is generally incorrect.

Example Considered: The North Sea

Applicability to the SAOS region: The model could be adjusted to the SAOS region.

Cost to Run: Unspecified, but probably not an overriding factor.

Error Estimate: Probably upwards to 200 percent depending upon the input residual current and wind factor.

2.1.2.7 Title: OILSIM

Author: Det Norske Veritas

Source: Technical Report, Det Norske Veritas, Research Division, P. O. Box 300, 1322 Hovik, Norway.

Description: OILSIM is a computer program which attempts to simulate the drift and spreading of oil slicks on the sea surface. It is intended for use in 1) risk analysis, 2) location of oil spill contingency centers, and 3) the assistance in cleanup operations. The program considers both physical and chemical effects. Physical modeling includes a drift based upon wind and mean currents, and spreading based upon gravity, viscosity and surface tension theory. Chemical modeling includes evaporation and weathering. Improvements in modeling are presently being worked on.

Input: Input includes the spill location, rate, duration, meteorological data base, and mean currents.

Procedure: The drift velocity vector is modeled by multiplying the wind velocity by a constant wind factor (2.5% - 2.7%) and rotating the vector by 12° - 15° to the right to account for the Coriolis deflection. The resulting wind drift is added to a mean current derived from drift card experiments. Seasonal variability is accounted for by using eight different mean current fields. Slick spreading is modeled in accordance with gravity, viscosity, surface tension theory in which gravity and inertia are initially controlling, followed by gravity and viscosity, and finally by surface tension and viscosity. Chemical effects include evaporation and weathering in the form of:

$$\frac{dQ}{dt} + \lambda Q = q \left[1 - f(t)\right]$$

where Q = oil volume on the surface, q = flow rate, f(t) = evaporation function and λ = breakdown coefficient for weathering. The model outputs the oil slick form and position.

Limitations: The wind factor and rotation may be subject to errors of a factor of 2. The manner in which the winds are calculated and sampled are crucial. Gravity, surface tension, viscosity theory for spreading is probably insufficient, as turbulence has been shown to be very important. Weathering is poorly understood at present.

Example Considered: The model was applied to the Phillips Petroleum, Bravo Platform, Ekofisk field spill.

Applicability to the SAOS Region: The model could be adapted to this region.

Cost to Run: Unspecified.

Error Estimate: Could be as high as 100 percent depending upon the input variables, the wind factor and the treatment of spreading and weathering.

2.1.2.8 Title: An Oilspill Risk Analysis for the South Atlantic Outer Continental Shelf Lease Area

Authors: Slack, J. R. and Smith, R. A.

Source: US Geological Survey, Open File, Rep. #76-653

Description: A computer simulation is used to analyze the risk that oil spilled from a lease area or a transportation accident would impinge upon the coast. The probability of a spill, the trajectories of a slick, and the relation to biologically and recreationally important areas are considered. Probabilities of risk occurrence are obtained from published literature. Slick trajectory simulation follows from the vector addition of a wind drift and a mean current. The wind drift is computed with a wind factor of 3.5 percent and a deflection angle of 20° to the right of the wind vector. The winds are obtained from first order

Markov process transition matrices for each of the 4 seasons, compiled using 7 years of data from Jacksonville, FL and Charleston, SC. The matrices are sampled every 3 hours. The mean current data were derived from published drift bottle data. The model does not include spreading or chemical aspects of a slick degradation.

Input: The inputs to the trajectory model include an initial location and a wind transition matrix.

Procedures: A 1 N.M. square grid is used. Trajectories are computed via vector summation at 3 hourly intervals. A total of 22,000 trajectories were computed covering 8 lease sites and 3 transportation routes over 4 seasons.

Limitations: The model does not consider spreading or chemical effects. Advection is subject to error on the order of a factor of 2 or more due to the use of drift bottle data for mean current and inadequate wind data.

Example Considered: SAOS region.

Cost to Run: Unspecified

Error Estimates: Upwards to 100 percent depending upon mean current and wind drift uncertainty.

2.2 WATER COLUMN MODEL EVALUATION

The objective of this evaluation is to determine which numerical model, if any, is capable of predicting the current field in the SAOS region. Before proceeding to the evaluation, the theoretical limits to forecasting currents in this region will be considered.

2.2.1 Special Considerations

The primary limitation on modeling regions like the SAOS area lie in the boundary conditions on the open fluid boundary. For a closed basin, with a good forecast of atmospheric wind stress and heat transfer to the ocean no trivial task in itself, and with a good parameterization of turbulent mixing, a primitive equations model could, in principle, forecast the current and density structure since all the forcing functions are given. For a region which has open fluid boundaries, the result is different. If all the forcing for the flow in the region under consideration is localized, i.e., occurs in that region, the fluid boundary conditions must simply allow disturbances to pass through the numerical boundary. On the other hand, and this is certainly true for the SAOS region, if forcing outside the rgion under consideration produces significant variations in the fluid boundary conditions of the SAOS area, and, as we know, the effect of varying boundary conditions can have significant impact several hundred kilometers into the region, then the best that can theoretically be achieved is a hindcast model. By this, it is meant that if conditions on the fluid boundary were known over a certain period of time, then prediction of what would have occurred inside the region can be made during that time period, i.e., hindcast could be achieved. The inability to forecast boundary conditions on the fluid boundary imposes a primary limitation on the predictive capability of any model. The more sophisticated the model, i.e., the more nonlinear its dynamics, the more serious the errors due to misspecifications of the boundary conditions. Let us say that it is desired to predict the quantity u which is subject to the following conditions:

$$\frac{d^2u}{dt^2} + u = \varepsilon u^3, \; u(o) = 0, \; \frac{du}{dt} = a, \quad \varepsilon << 1$$

the exact solution is:

$$u = a \cos t + \varepsilon u^3 \; f_1(t) + o(\varepsilon^2)$$

If we guess at a value of a, say a_g, the error for a linear model ($\varepsilon = o$) is:

$$u = u_g = (a - a_g) \cos t + \varepsilon a^3 \; f_1(t) + o \; (\varepsilon^2)$$

and for a nonlinear model:

$$u = u_g = (a - a_g) \cos t + \varepsilon(a^3 - a_g^3) \; f_1(t)$$

if $a_g > 1.3a$, then the "sophisticated" model is actually less accurate than the simple model. In general, the more poorly known the boundary conditions, the simpler should be the model chosen so that uncertainties are not amplified by the model.

A second and equally important limitation on the predictive capability for any model for the SAOS region is as follows: The SAOS region is strongly influenced by Gulf Stream process, i.e., Gulf Stream meanders, intrusions, filaments and rings. The Gulf Stream is a highly inertial baroclinic boundary current system, and as such, is subject to barotropic and baroclinic instabilities. The creation of filaments and rings and other eddy-like structures are most probably manifestations of these instabilities.

There are essentially two ways to obtain the desired statistical information on the frequency of occurrence, location, size, number and persistence of eddies and filaments. The first is through a long, intensive field program which would be expensive and require several years. The second technique would be to use a primitive equations model which could generate the desired statistics. This approach has several significant drawbacks, the most important of which are: the lack of a computer large enough to accommodate the calculations for the required time periods and the prohibitive costs. However, given that a primitive equations model were used, the best results that could be anticipated would be for annual, or perhaps seasonal, means, and would say nothing of the velocity structure of any single eddy or filament. This task is like trying to predict the instantaneous, rather than the mean flow in a turbulent fluid which is an impossible task. It is therefore emphasized that there is questionable value in using a sophisticated numerical model which takes into account the types of instabilities associated with the Gulf Stream as opposed to a less sophisticated, but more readily verifiable diagnostic model for the South Atlantic OCS region.

The sediment-water column boundary conditions used by water-column modelers are adequate for many circulation analysis purposes, but to actually input bottom boundary conditions, which are based on fact, to water column models is now not possible. The NSF-sponsored SANDS program, and other allied programs, will greatly enhance our ability to establish such conditions in the future.

In the following section, detailed qualitative evaluations are presented, and in a later section (5.2) recommendations for modeling the SOAS region are discussed.

2.2.2 Detailed Qualitative Evaluation of Selected Interior Water Column Models

Title: A Mathematical Model of the Indian Ocean

Author: M. D. Cox

Source: Deep Sea Research, Volume 17(1), 1970

Description: A time dependent baroclinic prognostic, primitive equations model is developed and run for 192 years with very coarse resolution used for the first 185 years and 1° square resolution used for the final 7 years. The temperature at the surface is a specified function of time (season) and the salinity is fixed. The rigid lid condition is used with $\psi = 0$ at open boundaries. The eddy viscosities are taken to be constants with $A_{J_{min}} = 5 \times 10^{7}$ $cm^2\ sec^{-1}$.

Input: Wind stress, surface temperature and salinity.

Limitation: The fluid boundary conditions, coarse resolution, and high horizontal mixing coefficients limit the applicability of the model, as does the specification of the surface density.*

Example Considered: Indian Ocean

Applicability to SAOS Region: Not applicable due to specification of surface density and simple fluid boundary conditions.

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*NOTE: By specifying the surface density, the underlying field is more strongly constrained than if a heat flux law were used. The model is then somewhat more diagnostic than predictive. Coarse resolution is often necessary in time dependent models because of monetary constraints, whereas in steady calculations, finer resolution does not cause a dramatic increase in cost.

Applicability to Other Coastal Regions: See above.

Cost to Run: Moderate

Error Estimate: The coarse resolution eliminates the small scale features which comprise the motion of the SAOS region.

Title: A Numerical Model of Coastal Upwelling

Authors: Journal of Physical Oceanography, Volume 2(1), 1972

Description: A two layer time dependent model incorporating the effects of bottom topography and horizontal mixing is developed. The problem considered is two-dimensional and an internal friction coefficient is used to parameterize internal friction. The surface is free. A semi-implicit scheme is utilized to allow a large time step.

Input: Wind Stress

Numerical Procedure: A semi-implicit scheme is used for the offshore velocities and the layer depths and longshore velocities are computed in a straightforward manner.

Limitations: Two-dimensionality and the poorly known internal friction coefficient and the simple outer boundary conditions limit the utility of this model.

Example Considered: Oregon Coast

Applicability to SAOS Region: Not applicable due to simplicity of boundary conditions, two-dimensionality, and shallow shelf in the SAOS Region. A closed basin is considered with no normal volume flux; this is inappropriate to the SAOS Region.

Applicability to Other Regions: May be applicable to other regions for short time scales and deep shelves.

Cost to Run: Small

Error Estimate: The error in the driving force is proportional to $\Delta C_i \tau_y t^2/h_i^2$ where ΔC_i is the uncertainty in C_i, the internal friction coefficient, t is time and h_i is the upper layer thickness.

Title: A Numerical Calculation of the Circulation in the North Atlantic Ocean

Authors: Holland, W. R. and Hirschman, A. D.

Source: Journal of Physical Oceanography, Volume 2(4), 1972

Description: A three dimensional time dependent diagnostic (density fixed and specified) model is developed. The eddy viscosities are taken to be constants, the rigid lid approximaton is used, and the model is run to steady state. An operator governing the stream function is obtained and solved at each time step by over-relaxation. Three experiments are performed: a homogenous-topographic run; a baroclinic flat bottom case; and a baroclinic topographic case. In the last case Gulf Stream transport is strongly enhanced. ψ is specified on the open boundaries.

Input: Wind stress and density field

Numerical Procedure: Over-relaxation at each time step.

Limitations: Coarse resolution and constant eddy viscosities limit the utility of this model.

Example Considered: North Atlantic from 10.5°S to 40.5°N

Applicability to SAOS: No boundary conditions are specified on seaward boundary of SAOS region so model is not totally specified with respect to SAOS region. It is potentially useful with modifications; specifically the boundary conditions would have to be reformulated.

Applicability to Other Regions: See above.

Cost to Run: Modest compared to predictive models.

Error Estimate: Coarse resolution eliminates many mesoscale features.

Title: Calculations of Flows in a Baroclinic Ocean: Numerical Methods and Results

Authors: Marchuck, G. I., Sarkisyan, A. S., Kochergin, V. P.

Source: Geophysical Fluid Dynamics, Volume 5(1), 1973

Description: A baroclinic model incorporating bottom topography and a time dependent density field is developed. The momentum equations are steady and linear and the density equation is time dependent. A linear elliptical equation governing the stream function is developed which involves the wind stress and density fields. The density is fixed at the surface, and in deep water, but is allowed to adjust between these levels. The stream function is taken to be zero at the boundaries and the model is run to steady state.

Input: Wind stress and surface densities.

Numerical Procedure: The equation for the stream function is solved by block relaxation.

Limitations: The momentum equations are linear and the stream function vanishes at the boundaries.

Area Considered: North Atlantic

Applicability to SAOS Region: The boundary conditions on the fluid boundary cause this model to be inapplicable to this region.

Applicability to Other Coastal Regions: See above.

Cost to Run: Moderate

Error Estimate: The coarseness of the grid implies that the features we would wish to resolve cannot be resolved.

Title: Baroclinic and Topographic Influence on the Transport in Western Boundary Currents

Author: W. R. Holland

Source: Geophysical Fluid Dynamics, Volume 4(2), 1973

Description: A three dimensional, time dependent baroclinic model is developed. The eddy viscosities are constant and the surface field is prescribed It is demonstrated that the combined effects of baroclinicity and bottom topography can bring the total Gulf Stream transport closer to observation than theories which neglect both of these effects through the mechanism of bottom torque which acts in the same sense as the wind stress curl.

Input: Wind stress and surface density.

Numerical Procedure: Similar to that of Cox (1970).

Limitations: This is a model for the North Atlantic and the open boundary is the equator where symmetry conditions are imposed.

Example Considered: North Atlantic from the equator to 62°N.

Applicability to SAOS Region: Boundary conditions not specified for a true open boundary, hence model is inapplicable.

Applicability to Other Regions: See above.

Cost to Run: Moderate due to coarse grid. Would be expensive on grid scale necessary for SAOS Region.

Error Estimate: Mesoscale features cannot be resolved.

Title: Verification of Numerical Models of Lake Ontario: Part I. Circulation in Spring and Early Summer.

Author: T. J. Simons

Source: Journal of Physical Oceanography, Volume 4(4), 1974

Description: A four layer prognostic model for the flow in Lake Ontario is developed and tested against observations. The surface is free and the momentum equations are linear. The barotropic free surface mode is decoupled from the internal mode and a short time step is used on the former mode.

Input: Wind stress and heat flux

Numerical Procedure: The internal and free surface modes are decoupled. Central differences in time are employed for pressure divergence terms and forward differences are used for friction diffusion terms. Nonlinear terms in the temperature equations are created by a Lax-Wendroff scheme.

Limitations: A large number of frictional parameters are available for specification, the model is linear, and a closed basin is considered.

Example Considered: Lake Ontario

Applicability to SAOS Region: No open fluid boundary conditions are used in this model. Hence, it is inappropriate.

Applicability to Other Regions: See above.

Cost to Run: Moderate

Error Estimates: Errors in speed as large as 100 percent are often encountered when model results are compared to field data.

Title: Development of a Simplified Diagnostic Model for Interpretation of Oceanographic Data

Author: J. A. Galt

Source: NOAA Technical Report ERL 339-PMEL 25 June 1975

Description: An elliptic equation governing the sea surface elevation is obtained under the assumptions of steady flow with negligible inertial accelerations. The density field and wind are required inputs. The equation is similar to that of Hsueh and Peng (1978). The sensitivity of the solution to boundary conditions is discussed and it is shown that errors in the surface elevation on the open boundary can lead to large errors in the solution. The author then proposes to determine the appropriate boundary conditions by measuring surface elevation along a single line running from shallow to deep water and then integrating changes in surface elevation along isobaths back to the boundaries while neglecting bottom stress effects. This proposed method of obtaining boundary conditions can lead to significant errors, since, as mentioned previously, the solution is extremely sensitive to boundary conditions (see below, Error Estimate).

Numerical Procedure: None specified.

Limitations: Inertial accelerations are neglected and an inappropriate method of obtaining boundary conditions is specified.

Region Considered: Northeast Gulf of Alaska.

Applicability to SAOS Region: Inapplicable due to errors in boundary conditions (see below) although the governing equation is satisfactory.

Applicability to Other Regions: Same problems apply to other regions as noted for SAOS Region.

Cost to Run: Unspecified as no numerical procedure is outlined.

Error Estimate: Let ζ_0 (d) be the measured elevation along an interior cross-shelf section. The author neglects bottom friction effects to obtain ζ on the boundary. Therefore, the error in the specified value of ζ on the boundary in the absence of baroclinic effects will be on the order of:

$$\zeta_{error} \simeq D_0 dd \int s_B \; |\nabla d| \, ds \; + \; D\zeta_0 \; d \int s_B \; \nabla_H^2 d \; ds$$

where the integrals are calculated along isobaths and ds is an element of arc length along the isobath, $|\nabla d|$ the slope, $\nabla_H^2 d$ the Laplacian of the depth, D the bottom Ekman depth, $\zeta_0 d$ ($\zeta_0 dd$) the first (second) derivatives of the measured elevation along the cross-shelf section, and s_B the distance to the boundary along an iosbath. If $\zeta_0 d$ 10^{-3}, $|\nabla_H^2 d|$ 10^{-8}/cm, s_B 200 km, then, error$\simeq$20 cm. This error is comparable to the specified ζ_0(d)(d) and renders this approach to obtaining boundary conditions from interior measurements totally useless.

Title: A Three Dimensional Simulation of Coastal Upwelling Off Oregon

Authors: Peffley, M. B. and O'Brien, J. J.

Source: Journal of Physical Oceanography, Volume 6(2), 1976

Description: The model is identical to that of O'Brien and Hurlburt (1972), except that it incorporates a beta effect and three dimensionality.

Input: Wind Stress

Numerical Procedure: A semi-implicit scheme is used in the offshore direction, an explicit scheme is used in the alongshore direction. No-slip conditions are applied at eastern and western boundaries and the quasi-symmetric condition developed by Hurlburt is used on the northern and southern boundaries.

Limitations: The internal stress coefficient is poorly known and limits the validity of the results to a few days.

Example Considered: Oregon Coast

Applicability to SAOS Region: The open boundary conditions are totally inappropriate to this region. The shallow shelf also limits the applicability of the model.

Applicability to Other Regions: Applicable to deep shelves without strong boundary currents.

Cost to Run: Small compared to prognostic level models.

Error Estimate: See review of O'Brien and Hurlburt

Title: A Numerical Model of the Somali Current

Authors: Hurlburt, H. E. and Thompson, J. D.

Source: Journal of Physical Oceanography, Volume 6(5), 1976

Description: Model is identical to that of Peffley and O'Brien, but is applied to west coast of South America.

Title: Numerical Simulation of the Gulf Stream and Mid-Ocean Eddies

Authors: Semtner, A. J. and Mintz, Y.

Source: Journal of Physical Oceanography, Volume 7(3), 1977

Description: A nineteen year integration in time of a primitive equation rigid-lid hydrostatic approximation model was performed using Laplacian (19 years) and biharmoic forms (3 years) for the horizontal mixing. Five levels of varying thickness in the vertical and rectangular boxes 75 (37) kilometers on a side were used for 15 1/2 (3 1/2) years in the horizontal. Large values of A_H were necessary to control computational noise, and excessive damping of eddy structures occurred for the Laplacian experiment. The biharmonic damping allowed for a more reasonable eddy structure and control of computational noise. Calculation of transformation of energies from the mean to the eddies were performed. A simplified shelf-slope topography was used.

Input: Wind stress and heat flux. A free-slip condition was used at lateral boundaries.

Numerical Procedures: Integration through time of the primitive equations.

Limitations: The rigid-lid approximation will produce errors at "high" frequencies.

Region Considered: East Coast of the United States

Applicabilty to SAOS Region: The biharmonic damping and method of including topography should be useful features of this model if one were building a time-dependent (prognostic) model of the SAOS.

Applicability to Other Regions: See above.

Cost to Run: 16 computational hours/year on IBM 360/91 for 37 kilometre grid.

Error Estimate: Over the large time scale considered, changing the mixing process (from Laplacian to biharmonic) changes the results completely so no specific error can be assigned.

Title: A Semi-Implicit Model for Baroclinic Oceans

Authors: Madala, R. V. and Piacsek, S. A.

Source: Journal of Computational Physics, Volume 23 (2), 1977

Description: The full non-linear, time dependent equations of motion are vertically averaged to obtain one set of equations for the free surface elevation and the mean horizontal velocities, and another set for the vertical fluctuations of velocity about the mean for the baroclinic pressure field, and for the temperature and salinity fields; the vertical eddy coefficients are taken to be Richardson number dependent functions. The first set of equations are treated implicitly, and yield an elliptic equation for the surface elevation at each step. The implicit treatment of this set allows for a larger time step than would an explicit calculation as the free surface model contains rapidly traveling surface gravity waves. The second (baroclinic) set of equations are treated explicitly as the natural time scale is much larger than for the barotropic free surface mode. Fifteen levels of variable thickness are used for a total depth of 1.7 kilometres and a horizontal grid of 30 kilometers is used. The depth is assumed to be constant, the surface elevation is assumed to decay at infinity, and the stress at the bottom is taken to be zero.

Input: The initial density and velocity fields, the atmospheric pressure and wind stress.

Numerical Procedures: Solutions are obtained by marching forward with time, and the elliptic equation for the surface elevation is taken to be zero at infinity, and the bottom stress is taken to be zero which would not be valid in shallower water than that considered in the model.

Example Considered: A comparison between the semi-implicit and directly explicit time schemes for a stationary hurricane is undertaken to compare accuracies and time savings.

Applicability to SAOS Region: Due to the constant depth, zero bottom stress and condition at infinity, this model is not applicable to SAOS Region. However, with a relaxation of these conditions, the model could prove useful.

Applicability to Other Regions: See above.

Cost to Run: A time savings of a factor of twelve over directly explicit schemes is achieved.

Error Estimate: Errors on the order of 10 percent between the schemes were realized. This model, with modifications looks very promising.

Title: A Three Dimensional Model of Lake Ontario's Summer Circulation I. Comparison with Observations

Author: J. R. Bennett

Source: Journal of Physical Oceanography, Volume 7(4), 1977

Description: An eight level time dependent rigid-lid model is developed to study the flow in Lake Ontario. The Munk-Anderson relations are used for the vertical mixing coefficients. The momentum equations are taken to be linear and a vorticity equation for the stream function is solved at each time step.

Input: Wind stress and heat flux.

Numerical Procedure: An estimate of the horizontal velocity is made at the new time neglecting the barotropic pressure gradient. The new value of the stream function is calculated and the horizontal velocities are then corrected. The vertical velocity and temperature at the new time step are then calculated.

Limitations: The momentum equations are linear, the rigid-lid approximation is used, and the basin is closed.

Example Considered: Lake Ontario

Applicability to SAOS Region: Due to the fact that the basin is closed, the model is not applicable to the SAOS Region.

Applicability to Other Regions: See above.

Cost to Run: Small for a predictive level model.

Error Estimate: Errors on the order of 100 percent occur when compared to field data.

Title: The Linear Decomposition of a Diagnostic Shelf Circulation Model and Discussion of Alternate Boundary Condition Formulations

Author: Galt, J. A. and Watabayashi, G.

Source: Numerical Studies - PMEL, Report to OCSEAP, September 1978, RU#140

Description: A steady linear baroclinic diagnostic model is discussed. The model starts with a fairly standard vorticity equation in terms of the free surface elevation and density fields which reflects the fact that the vertical velocity at top and bottom are equal. The equation is elliptic and requires boundary conditions at the coast, in deep water, and at two cross-sections along the shelf. We note that the velocities across the cross shelf boundaries reflect the forcing in regions outside that under consideration, and are generally important especially in the SAOS Regions. Since the data on these boundaries are not available, the authors resort to various subjective ad hoc artifices to avoid specifying the physically and mathematically necessary boundary conditions. For the wind driven response, it is observed that the cross-shelf surface slope may be a constant across the shelf. The velocity equation is solved with this condition satisfied at one cross-section. The resulting solution has the slope constant across this cross-section, but not elsewhere. Six of these "hinge" solutions are then added together to yield the purported wind-driven velocity field. The result which starts with the basic assumption that the cross-shelf slope is a constant, ends with a solution which does not satisfy this condition. Further, the choice of hinges is arbitrary and the velocity distribution for various choices of hinges are not compared. For the baroclinic solution one alternative taken is to choose boundary conditions at the cross-shelf boundaries such that the potential energy associated with the free surface due to the density structure is minimized. Now the potential energy associated with the density field itself is not minimized (the isopycnal surfaces are not flat) so why should the potential energy associated with varying the free surface be minimized; any small variation of the density structure would cause a larger energy variation than would a large change in surface elevation. These ad hoc "principles" are required to replace the very real need for boundary conditions. The results must then be viewed with extreme skepticism.

Input: Density and wind fields.

Numerical Procedures: Green's function solutions corresponding to "hinge" solutions and boundary point input are developed and utilized to minimize the potential energy.

Example Considered: The northeast Gulf of Alaska

Applicability to SAOS Region: Totally inapplicable as physical boundary conditions cannot be incorporated in the model.

Applicabilty to Other Regions: See above.

Cost to Run: Small

Error Estimate: Since the results depend on the eye of the author, i.e. are very subjective, this cannot be estimated.

Title: A Numerical Model of the depth-Dependent Wind-Driven Upwelling Circulation on a Continental Shelf

Authors: Hamilton, P. and Rattray, M. Jr.

Source: Journal of Physical Oceanography, Volume 8(3), 1978

Description: A two-dimensional multi-level time dependent non-linear, free surface, primitive equations model is developed to study upwelling over a continental shelf. The wind is impulsively switched on initially, and the density flux is zero at the top, bottom, and coast. Horizontal mixing is retained in the density equation, but dropped in the momentum equations. The Munk-Anderson formulae are used to determine the vertical mixing coefficients.

Input: Wind stress and an initial density field.

Numerical Procedure: The numerical method is semi-implicit, using forward and backward differences in time and centered differences in space.

Limitations: The model is two-dimensional.

Example Considered:: 21°40'N of Northwest African Coast.

Applicability to SAOS Region: Inapplicable due to two-dimensionality of model.

Applicability to Other Regions: See above.

Cost to Run: Moderate compared to other free surface models.

Error Estimate: Fifty to one-hundred percent error as compared to observations.

Title: The Role of Mesoscale Eddies in the General Circulation of the Ocean--Numerical Experiments Using a Wind-Driven Quasi-Geostrophic Model

Author: W. R. Holland

Source: Journal of Physical Oceanography, Volume 8(3), 1978

Description: A two-layer constant depth, time dependent, rigid-lid, model is developed. The horizontal velocity is taken to be quasi-geostrophic, vorticity equations in each layer and an equation for the vertical velocity is obtained. Elliptical equations in space for the time derivative of the difference of the stream functions as well as the mean streamfunction are then solved. The roles of bottom dissipation and lateral mixing, both Laplacian and biharmonic in the energetics are then examined. The quasi-geostrophic, two-layer approach allows for finer horizontal resolution in a given time than does a multi-level model. The model is run to a statistical steady state.

Input: Wind stress

Limitations: Topography is neglected.

Example Considered: A model ocean basin with dimensions 1000 kilometres in the east-west and 1000 or 2000 kilometres in the north-south direction.

Applicability to SAOS Region: Since topography and shallow shelves are factors in this region, the model is not applicable.

Applicability to Other Regions: See above.

Cost to Run: Small compared with primitive equation models.

Error Estimate: The results strongly depend on the choices of frictional coefficients and hence the errors are indeterminant.

Title: A Hindcast Model of Barotropic Response over the Oregon-Washington Continental Shelf During the Summer of 1972

Authors: Hsueh, Y. and Lee, C. Y.

Source: Journal of Physical Oceanography, Volume 8(5), 1978

Description: A time dependent hindcast model for the barotropic response of continental shelf waters to wind and boundary conditions is developed. The model is linear, barotropic and geostrophic in the offshore momentum equation. Vertical velocities induced by bottom boundary suction are incorporated into the model. The basic assumption is that derivatives in the longshore direction are small compared to offshore derivatives. A linear equation governing the time development of the bottom pressure is solved numerically.

Input: Wind stress and bottom pressure as a function of time on the equatorial boundary.

Numerical Procedure: The equation is integrated numerically by a scheme that involves marching forward in time and northward in the alongshore coordinate.

Limitations: The model is barotropic and linear and, and as originally formulated, cannot account for rapid variations in topography in the alongshore direction.

Example Considered: Oregon coast from 45° to 47°N.

Applicability to SAOS Region: Not directly applicable as alongshore gradients in topography can be as large as offshore gradients, i.e., the longwave approximation is invalid, but may be easily dropped. Recent unpublished modifications in which a P_{yy} term was added which represents pressure differentiated with respect to the alongshore coordinates twice. Therefore, if there are any rapid changes in topography in the alongshore direction, there will be associated changes in the pressure field. With these changes, the model becomes a prime candidate for application to the SAOS region in a diagnostic and quasi-prognostic mode, at least for the barotropic portion of the circulation.

Applicability to Other Regions: Will be applicable to regions with slowly varying alongshore topography.

Cost to Run: Small

Error Estimate: Approximately fifty percent of the observed alongshore current was predicted by this model.

Title: A Diagnostic Model of Continental Shelf Circulation

Author: Hsueh, Y. and Peng, C. Y.

Source: Journal of Geophysical Research, Volume 83(C6), 1978

Description: A governing equation for the bottom pressure is obtained and solved numerically subject to appropriate boundary conditions. The model yields the velocity field outside of boundary layers.

Input: Wind stress field, density field, and bottom pressure on the "southern" boundary.

Assumptions: The flow is steady, the Ekman layers are thin compared to the total depth so that the thermal wind relation is valid throughout most of the water column. Non-linear effects and horizontal mixing are neglected. The alongshore length scale is assumed much larger than the shelf width (this is a major limitation).

Numerical Procedure: Under the last assumption, the governing equation is essentially "diffusive" with the alongshore coordinate regarded as timelike. A fairly standard implicit scheme is employed to integrate the equations northwards, the direction of increasing "time".

Limitations: If the topography varies "rapidly" in the alongshore direction, the basic assumption is questionable. Also, if the longshore distance is long, the solution is non-uniform in y.

Region Applied To: Oregon Coast from 44°N to 45° N.

Applicability to SAOS: As currently specified, the model is inappropriate because of substantial changes in alongshore bottom depths. With the inclusion of $\delta(\cos\alpha)\,PB_{yy}$ in the equation, a reasonable model for "seasonal" currents would result, although a different numerical scheme would be necessary as the new equation is not "parabolic".

Applicability to Other Regions:

Should give reasonable "long term" averages if the topography does not vary rapidly in the alongshore direction and the "North-South" extent is not too large.

Cost to Run: Minimal

Error Estimate: From topographic variations = $10^6/Ly$

$Ly^{-1} = \frac{1}{H}\,Hy$ (cm)

From cumulative effect:

$(A/f)^{3/2} \quad H^3 \times W^4$

Title: A Coastal Ocean Numerical Model

Authors: Blumberg, A. F. and Mellor, G. L.

Source: Mathematical Modeling of Estuarine Physics, Springer-Verlag, Nov., 1978

Description: A three-dimensional, time dependent, baroclinic, topographically affected, free surface model using a vertically stretched coordinate is developed. The vertical mixing coefficients are taken to be functions of the turbulent kinetic energy and turbulent macroscale, which are predicted as well as the vertical gradients of velocity and density. The horizontal mixing coefficient is taken to be a small constant which requires a small horizontal grid. Vertically averaged and internal modes are decoupled which allows for a larger time step for the latter as opposed to the former calculation. Results are shown to be very strongly dependent on assumed fluid boundary conditions which weakens the predictive skill of this model.

Input: Wind stress, heat and salinity flux.

Limitations: A fine horizontal grid is required and the results depend heavily on accurate specification of boundary conditions.

Example Considered: Mid-Atlantic Bight

Applicability to SAOS Region: While this model has the most sophisticated treatment of mixing coefficients of all models considered, the influence of the fluid boundary conditions, which are poorly known, and significantly influence the flow in the SAOS region make the sophistication of the mixing coefficient treatment superfluous.

Applicability to Other Regions: See above

Cost to Run: Moderately expensive, comparable to other predictive models.

Error Estimate: Results at a point are very strongly dependent on boundary conditions.

Title: An Intergral Hydrodynamic Model of Upper Ocean Frontal Dynamics: Part I. Development and Analysis

Author: R. W. Garvine

Source: Journal of Physical Oceanography, Volume 9(1), 1979

Description: A steady two-dimensional integral model of an upper ocean front is developed. Similarity profiles of specified forms for the density and velocity fields are assumed. Ths mass flux, pycnocline depth and density variation are then solved.

Input: Velocity at infinity and turbulent length scale.

Numerical Procedure: Numerical marching in the cross-frontal coordinate.

Limitations: The assumptions of the shape of the velocity profile as well as the two-dimensionality of the model limit this quasi-analytical model.

Example Considered: A range of solutions is obtained.

Applicability to SAOS Region: Inapplicable due to two-dimensionality, lack of bottom topography, and large numbers of input parameters.

Applicability to Other Regions: See above.

Cost to Run: Small

Error Estimate: Results are very strongly dependent on the ratio of a dissipation length to the deformation radius which is essentially unknown and may vary from 0.1 to 10 in the ocean.

Title: A Dynamical Analysis of Currents Near the New Jersey Coast

Authors: Bennett, J. R. and Magnell, B. A.

Source: Journal of Geophysical Research, Volume 84(C3), 1979

Description: A two-dimensional, time dependent, multi-level, model for coastal flows is developed. Baroclinic effects and horizontal mixing are neglected. The onshore flux is assumed to increase linearly from the coast and is taken to be proportional to the local time derivative of the observed sea surface elevation. Longshore variations in the velocity field are neglected, a constant longshore pressure gradient is specified, non-linear terms are retained in the momentum equation and the eddy viscosity is proportional to the vertical shear and a function of depth.

Input: Wind stress and surface elevation.

Numerical Procedure: The time derivatives are evaluated by the Adams-Bashforth method for the advective terms, by forward differences for the diffusive terms and by the trapezoidal rule for the Coriolis terms.

Limitations: The model is two-dimensional and barotropic.

Applicability to SAOS Region: Inapplicable due to homogeneity and two-dimensionality.

Applicability to SAOS Regions: Applicable only for two-dimensional shelves within 10 kilometers of the coast.

Cost to Run: Moderate

Error Estimate: Model cannot reproduce rapid changes in currents which are observed and is totally inadequate for periods shorter than forty hours.

2.3 BOTTOM AND SEDIMENT TRANSPORT MODEL EVALUATION

Mechanics of bottom and sediment transport include the fundamentals of the physics of flow in a two-phase fluid (liquid phase and a granular or solid phase), fluid dynamic forces, forms of grain motion, and transport rates. The most important mechanical properties of the flow to be considered include the shear stress distribution, velocity distribution and roughness factors. The onset of movement of the bottom requires knowledge of the detachment of isolated grains, the critical stages of mobile beds, the detachment of mixed granular materials, and the parameterization of fluctuating and non-fluctuating lift forces.

Generally speaking, sediment transport models are unsophisticated in nature in comparison with models of the atmospheric planetary boundary layer or of the oceanic surface boundary layer. Fluid mechanical concepts describing the multi-phase fluid physics of the bottom boundary layer are somewhat deficient. Still, the insights provided by an extensive list of laboratory and, more recently, field observational studies, i.e., experimental, and empirical relations and analytical to numerical models provide a general basis for establishing a predictive capability. Given environmental variability, the more generalized solutions have application under the wider variety of conditions which exist in the South Atlantic Bight.

2.3.1 Special Considerations

It is useful to review the properties of bottom fluid and granular materials which usually are necessary as input or output checks for most of the models discussed as being useful in the South Atlantic Bight. These properties include: the fluid density, the dynamic viscosity, the grain density, grain size of mixture, grain size corresponding to mixture percentage, grain size relative to (or rather normalized by) the maximum grain size, the mixture percentage, grain weight in the fluid, grain size distribution curve, kinematic viscosity, specific weight of fluid, specific weight of grain in air, specific weight of grain in fluid, settling velocity, bottom slope, viscous shear stress, turbulent shear stress, shear velocity, bed roughness height, particle roughness height, boundary layer thickness, laminar sublayer thickness, total shear stress, total shear stress interacting between flow and flow boundary, Von Karman constant, and lower limit of validity of logarithmic velocity distribution.

Dimensionless coefficients which are variously used to define and model the transport of sediments include (in non-dimensional units): flow depth; density ratio of fluid and solid phases; mobility number; transport rate of H. A. Einstein; Froude number; Reynolds number in terms of average velocity; Reynolds number of flow at the bed; grain size Reynolds number; Shields function; and modified Shields function.

It is clear that to properly address the sediment transport parameters one must have a clear overview of the regional physical oceanography, the regional boundary layer mechanics, and the regional sediments and sediment transport parameters. Present field programs which deal directly with the sediment transport parameters are typically either purely physical oceanographic or geological in nature. The melding of the two disciplinary approaches has been attempted by few investigators, but the obviousness of the need for joint ventures in view of the present state of knowledge of the mechanics of the oceanic bottom has been appreciated and several individuals (J. D. Smith, University of Washington; G. Weatherly, Florida State University; W. Grant, Woods Hole Oceanographic Institute; O. Madsen, Massachusetts Institute of Technology; and others) are actually addressing all disciplinary aspects of the problem from geologic to physical oceanographic, and from field studies to modeling.

As pointed out by prior authors, physical oceanographic models usually attempt to parameterize the benthic boundary layer and then allow the flow to slip along whatever boundary is defined by the seabed. A logarithmic velocity profile, requiring a logarithmic functional grid is generated by the dynamics of wall turbulence, in a thin layer above the seabed. At the top of the log layer, one can then evaluate the bottom boundary shear stress through the inclusion of a drag coefficient which, in effect, linearizes the bottom boundary layer dynamics as far as the interior water column flow is concerned.

Sediment transport really involves two conceptually separate, but physically coupled, modes of transport: the suspended sediment load (SSL), and the near bottom mode, or bed load. If one deals strictly with the SSL mode, then the volume transport is related to that value of the shear stress which is in excess of that required to initiate motion of a sand grain, in multiplicative association with the value of the shear velocity taken to a power greater than unity. On the other hand, the Bed Load Transport (BLT) mode volume flux of sediments can be parameterized as either the shear velocity times the excess shear stress taken to the second power at low transport rates, or as the excess shear stress times the shear velocity at high transport rates. The difference in the BLT parameterization is a function of transport rates, with the former law used under "high" transport and the latter under "low" transport rates, respectively. In the

BLT, sediments move in a rolling flow in the immediate vicinity of the seabed, while in the suspended mode the sediments are thrown into suspension and effectively dispersed throughout a typically thick and occasionally well stratified layer. While the bed load moves at speeds less than that of the fluid, the suspended load moves at the same velocity as the surrounding sea water, though the sediment and the sea water do comprise a multiphase fluid which is linked to the momentum and energy balances through the pressure gradient. BLT in the marine environment historically has been predicted through the use of empirical and/or semi-empirical laws. These relationships have been developed through arduous laboratory testing and can usually be fitted to the marine environment at hand through the means of informed artistic license. As will be discussed further, the problem with these relationships is that the value of the local boundary shear stress, which is necessary to each of the laws, is not well known. SSL models all suffer from a lack of knowledge of the values of the suspended load at the bed load-suspended load interface. Therefore, the flux across that interface is also unknown. This value, usually expressed as a concentration, serves as a bottom boundary conditon for the suspended sediment transport (SST) equations. The best sources of accepted boundary shear stress relations for the BLT problem can be found in Swift, Duane and Pilkey (1972) and in Stanley and Swift (1976). From articles in these texts and other review articles, e.g., Smith (1977), it is clear that the sediment transport problem (STP) is further complicated by the fact that all of the models of the transport of sediments will ultimately suffer from incomplete knowledge of the instantaneous value of the shear stress under normal continental shelf conditions. Shear stress can be decomposed into tangential stresses (also known as skin friction or viscous drag) and normal stresses (also known as form or pressure drag) neither of which have been measured under the natural variability of the continental margin bottom relief.

The state-of-the-art in bottom sediment transport modeling is such that a reasonable idea of the patterns or trends could be discerned using existing data augmented with some simultaneous near bottom wave-current measurements. Greater specificity and sophistication of prediction techniques must await future field verification of some critical parameters and terms in existing models.

Models by Grant and Madsen (1978), Madsen and Grant (1977), Smith and McLean (1977), Weatherly and Martin (1978), and Weatherly and van Leer (1977), along with the Taylor and Dyer (1977) model, represent the state-of-the-art in sediment transport modeling. With regard to their applicability to the South Atlantic Bight, it is felt that they could be used in the SAOS region stress. The shear stress parameter could then be broken down further to obtain a skin friction value.

The models that are available can predict the movement of oil and sediment if certain assumptions regarding the behavior of oil droplets are made; namely, that the droplets will behave as sediment particles once the two have joined and that even if they do not, the oil particles, once they sink, will not become neutrally boyant at some level in the water column. There are a number of significant problems related to these assumptions. First, it is not clear that oil droplets do not, at some point in the weathering process, become neutrally buoyant and cease sinking; even if they are associated with sediment particles. The existing sediment transport models could accommodate the variability in density, but there is insufficient information regarding the actual behavior of such droplets. Second, the model would have to account for the variability in type of oil (or products) that was spilled along with certain environmental factors affecting the weathering characteristics of the oil. There is an additional, but critically important problem of not knowing how oil affects the threshold for initiation of sediment movement once the oil has been deposited on the bottom. These are important items that should be addressed in the future in order to better understand the role of sediment in dispersion of oil.

There are a limited number of models available to deal with bedform movement and effects of bedform movement on structures. In fact, there are no truly predictive models available, and the physics of such processes are known in a qualitative sense. Investigators at the Woods Hole Oceanographic Institution have been able to describe, again in a qualitative way, the movement of small-scale bed-forms (on the order of one meter in height) in areas of high tidal currents (two to three knots), but there are no known models available for describing the movement of bedforms on the continental shelf. Quite a bit of work has been done on the fluid flow over slowly varying topography, particularly in flume studies, but little has been applied to actual continental shelf situations.

BLM needs for sediment and bottom transport models in their environmental assessments basically include three applications of such models: in predicting the distribution of sediment particles that could come into contact with spilled oil from any source (the role of suspended sediment in fate of oil); in describing the bedform movement and scour as it is related to hazards to man-made structures on the continental shelf; and in predicting the distribution of potentially harmful material, e.g., drilling muds, emanating from a point source.

The generic problem of parameterization of the bottom boundary layer is inherent is all three types of models noted above (e.g., what are the effects of various roughness elements on drag coefficient?). Other factors that should be parameterized if sediment transport models are to be made usable for prediction in OCS environments include thickness of the viscous sublayer, frictional velocity (U_*), concentration of sediments at the bottom of the sediment transport layer, and thickness of the Ekman turbulent layer. What may be the most viable approach for the Bureau of Land Management, given their timeframe and the applied nature of the investigations, is to utilize a wave hindcasting model such as the one being done by the Waterways Experiment Station (Corps of Engineers, Vicksburg, Mississippi) to provide data on waves (high frequency component) and to couple that with mean current data (low frequency component) to determine a crude transport picture. Our evaluation indicates that to go beyond this type of effort, one would be getting involved in a long-term, expensive research effort such as the National Science Foundation's SANDS program. It is emphasized that one model can not do the job; it is more likely that elements from two or more would have to be combined to make an effective tool.

It is clear that models must be sufficiently general and reasonably well parameterized so that as advances are made, relevant models do not need to be discarded completely; rather merely updated. The sediment transport problem has a definite feedback to the establishment of a bottom boundary condition for water column models. Of course, the type of water column model(s) applicable to the Bureau of Land Management needs may not be able to effectively use such sophisticated bottom boundary input.

The most pressing problem is the adequacy of the available data to verify existing theory. Although there has been considerable data collected on the concentration of suspended sediment on the continental shelves of the United States (particularly on the Eastern US Continental Shelf), much of the data are of limited value for the calibration of sediment transport models because the instruments used have inherent measurement weaknesses (e.g., the transmissometer), especially in their inability to establish quantitative values for suspended sediment. There is also a problem resulting from the level in the water column at which suspended sediment measurements are made. The height above the bottom commonly used for placement of the transmissometer is one meter, which may be above the level attained by resuspended sediment. It is difficult to differentiate between locally suspended sediments and those which are advected into the local region, thereby raising significant uncertainties in the mechanisms of sediment transport. There is also a lack of simultaneous measurements of high frequency (time scales directly relevant to sediment resuspension) and low frequency (current) components in the system.

It should be pointed out that the data collected in the SAOS region by Butman and other USGS personnel do have applicability at the lowest level in the prediction of the transport of sediments. That is: trends in sediment transport can be discerned; significant events affecting the threshold of sediment movement can be identified; length scales of events can be determined which are useful in determining sampling grid size; and, a sense of the relative importance of various sediment transport mechanisms can be obtained.

It is our concensus that at the present time theory is advanced beyond capabilities to make field measurements of critical parameters. It is, for instance, unclear how to separate skin friction from total stress; therefore, it is difficult to verify the applicability of laboratory criteria for sediment movement (e.g., Shields parameter). In order to establish a sound data base for sediment transport in the benthic boundary layer, it will be necessary to obtain time series of total shear stress at the appropriate scale. In addition, it will be necessary to obtain definitive information on the vertical structure of turbulence in the water column in order to upgrade existing models.

There are really three sets of scales of interest in sediment and bottom transport modeling: for initiation of sediment movement, on the order of sediment grain size; for the transport of sediments, on the order of size of bedforms and over the scale of wave fields; and for the purpose of modeling, spatial averages of skin friction and average sediment size over a distance commensurate with the model of interest.

Sophisticated measurements of the shear stress in a special case (i.e., a viscous sublayer over a smooth bed) in the benthic boundary layer have been made by Caldwell, of Oregon State University, using a hot film technique. His measurements are reliable at the 95 percent level, but are of limited direct interest to sediment transport. These measurements show, however, that some of the concepts developed in the laboratory are applicable in the field. The major question is how accurately does one need to know bottom stress in order to make useful predictions for the problems of concern to the Bureau of Land Management.

There are computer models available (see, for example, Weatherly and Martin, 1978) that utilize existing wave climate, currents, and grain size distribution data to describe sediment transport. These are limited by the reliability of the benthic boundary layer stress values that are used and the input data. Therefore, while the solutions are quantitatively correct, there is no way to verify the agreement of the results with natural conditions. As discussed previously, the benthic boundary layer models can provide input to the water column models in the form of a "bottom" boundary condition.

The input of water column models to benthic boundary layer models has been shown to be feasible by a number of investigators, including Smith and McLean (in press), Madsen and Grant (1979), and Taylor and Dyer (1977). There are no real problems with computer interfacng either, since the output from one model can be used as input to another and is generally in the form of one or two terms easily inserted in the benthic boundary layer model. Coupling threshold models to bed load models to suspended sediment models to wave-current models to determine ultimate dispersal is technically feasible. It would be difficult, however, to obtain field verification of such a hierarchy of models.

The flow of water and sediment transport in the bottom boundary layer depends to a large extent on the flow in the water column just above the bottom, the bottom roughness, and sediment grain size. Near-bottom flow and sediment transport have been modeled (see, for instance, Grant and Madsen, 1978, Madsen and Grant, 1979, Weatherly and Martin, 1977, Adams and Weatherly, 1978, and Taylor and Dyer, 1977), but all model results are qualified by the reliability of certain terms such as critical shear stress and skin friction. Our conclusion is that modeling is far in advance of field verification measurements, and that the reliability of model output is a function of the quantity and quality of model input such as interior water column velocity vectors. This requirement closely links the bottom boundary layer models with the interior water column models.

At the present time only rudimentary laboratory models are available to predict the movement of bed forms on the continental shelf. Extensive work using laboratory flumes has been done on flow over slowly varying topography, but the applicability of these studies to the shelf is unclear. Considerably more field work must be performed before confidence can be gained in those models that do exist.

Up until a few years ago, most sediment transport models were either empirical in nature with little hydrodynamics in them or they were purely theoretical with little input from field data. Few, if any, of the theoretical models had ever been field tested, and when new observations were made that were in conflict with the empirical models, the models were adjusted or "fine-tuned" to yield better agreement. There have been many theoretical treatments of sediment transport in fluid flow (see, for instance, Kuenen and Middleton), and laboratory flume studies (by Hand, Middleton, Kuenen and many others) which were designed to study bedform changes, initiation of grain movement, modes of sediment transport, and small-scale fluid dynamic-sediment interactions. In addition, there has been a significant amount of work done on the theoretical, experimental and practical aspects of sediment transport in the surf zone and shallow nearshore areas with particular emphasis on beach protection (e.g. work by Inman, Bagnold, and Longuet-Higgins). Recent models such as those by Grant and Madsen, Madsen and Grant, Smith and McLean, Weatherly, and Taylor and Dyer have placed more emphasis on the application of hydrodynamics theory to sediment transport with subsequent field verification. In effect, they are treating shelf sediment transport in a more basic physical sense. The problem lies in the field verification of critical terms in the models such as total shear stress and skin friction. Given that the values for these terms were reliable, in a real world sense, the predictions would be exact.

Recently there have been two significant, concerted efforts at solving some of the engineering and experimental problems related to field verification of some of these more physically sound sediment transport models. The first of these is called SANDS (Shelf and Nearshore Dynamics and Sedimentation) and is under the directon of the National Science Foundation. It will concentrate on the problems related to shelf sediment dynamics and will be fully underway toward the end of 1979. The second of these, HEBBLE (High Energy Benthic Boundary Layer Experiment) is sponsored by NASA and will concentrate on the study of the benthic boundary layer primarily in the deep ocean. It covers all aspects of the problem of sediment entrainment, transport, and deposition and attempts to deal with theory, engineering, and experimental problems. Although neither of these programs is fully-funded yet, it is likely they will be. Even if they were not, however, the preliminary planning and workshop sessions of both have separately addressed many of the key questions in a logical and thorough manner, and could serve as a comprehensive framework for future sediment transport mechanism studies in the marine environment.

2.3.2 Detailed Qualitative Evaluation of Selected Bottom and Sediment Transport Models

Title: Stromungsgesetze in rauhenrohren

Author: J. Nikuradse

Source: VDI-Forschungsheft. Beilagezu Forschung auf dem Gebiete des Ingenieurwesens, Ausgabe B., 1933

Description: Describes the relationships between U_*, k_s, z_f, and υ, the frictional drag velocity, velocity associated with the bottom shear stress, the roughness element height, the roughness length and the kinematic viscosity, respectively, for hydraulically smooth, transitional and rough flow. Allows for the computation of the bottom roughness parameter z_f in a bottom boundary layer logarithmic velocity profile. Determines the bottom shear stress averaged over a few tens of grain diameters. Assumes a steady flow.

Input: Frictional drag velocity (U_*), size of roughness elements (k_s), and kinematic viscosity (υ).

Numerical Procedure: Direct hand calculation.

Limitations: Strictly applicable under steady flow conditions.

Region Considered: General application.

Applicability to SAOS Region: Possibly applicable during winter south of Cape Fear or during summer throughout the South Atlantic Bight when steady conditions prevail.

Applicability to Other Regions: Applicable under steady flow conditions.

Cost to Run: Minimal

Error Estimates: Essentially qualitative.

Title: Inception of Turbulence at the Bed under Periodic Gravity Waves

Author: J. I. Collins

Source: Journal of Geophysical Research, Volume 68, 1963

Description: Gives a relation for computation of critical Reynolds number for an oscillatory flow; i.e., a uniform unsteady flow; which can then be used in a computation of boundary shear stress. Assumes progressive gravity waves which are observed as simple oscillatory flow by the seabed.

Input: Ratio of particle to wave phase velocities and dynamic viscosity.

Numerical Procedure: Hand calculations

Limitations: Does not apply when flow is not simple oscillatory motion.

Region Considered: General

Applicability to SAOS Region: Applicable everywhere when dealing with motions defined as simple oscillatory, such as progressive gravity waves.

Applicability to Other Regions: General

Cost to Run: Minimal

Error Estimates: Guess

Title: Wave Boundary Layer and Friction Factor

Author: J. G. Jonsson

Source: Proceedings of the 10th Conference of Coastal Engineers, 1967

Description: Relation for friction factors involved in a computation of instantaneous boundary shear stress in studies of initial motion of sediment under wind waves. Assumes simple oscillatory flow.

Input: Ratio of particle to wave phase velocities and dynamic viscosity.

Numerical Procedure: Hand calculations

Limitations: Not applicable if flow non-simple oscillatory

Region Considered: General

Applicability to Other Regions: General

Applicability to SAOS Region: Within the spectrum of pure, simple, oscillatory motion; e.g., progressive gravity waves.

Cost to Run: Minimal

Error Estimtes: Guess

Title: Sediment Threshold Under Oscillatory Waves

Author: Komar, P. D. and Miller, M. C.

Source: Proceedings of the 14th Conference of Coastal Engineers, 1975.

Description: Confirmed results of Jonsson (1967) with regard to the shields diagram for initiation of sediment motion in a uniform, steady flow.

Input: Drag coefficient, kinematic viscosity, mean spacing distance of bed forms measured parallel to a streamline.

Numerical Procedure: Hand calculations

Limitations: Steady flow conditions

Region Considered: Massachusetts Coast, Columbia River

Applicabilty to SAOS Region: During winter South of Cape Fear or during summer in South Atlantic Bight, whenever steady flow conditions prevail.

Cost to Run: Minimal

Error Estimate: Uncertainty of approximately 150 percent in output values.

Title: A Numerical Study of Time-Dependent Turbulent Ekman Layers Over Horizontal Sloping Bottoms

Author: G. L. Weatherly

Source: Journal of Physical Oceanography, Volume 5(2) 1975

Description: Computation of boundary shear stress in uniform, two dimensional, unsteady flow. Equation governing uniform flow in vicinity of seabed due to wind generated waves and steady currents is a balance of the local time rate of changes of the current with the horizontal pressure gradient and vertical stresses. Can accommodate tides defined as poincare waves as well. Assumes flow is uniform and unsteady.

Input: Boundary conditions as the vertical coordinate goes to infinity and at the impermeable bottom from time greater than zero. Need value for eddy viscosity coefficient.

Numerical Procedure: Computer evaluation of regular functions.

Limitations: Flow is assumed to be uniform, unsteady and is two dimensional in space.

Region Considered: Applied to regions where waves prevail, are simple oscillatory and do not suspend sediments during a cycle.

Applicability to SAOS Region: In regions and in the part of the current spectrum where oscillatory flow superimposed on a background of mean flow is the rule.

Applicability to Other Regions: See above

Cost to Run: Fifty center per run on an IBM 370/165

Error Estimates: Minimal

Title: Spatially Averaged Flow Over Wavy Boundaries

Authors: Smith, J. D. and McLean, S. R.

Source: Journal of Geophysical Research, in press.

Description: Calculates a bottom roughness length through use of an empirical law. Assumes bottom roughness height linearly proportional to excess shear stress and inversely proportional to the difference between sediment and seawater densities.

Input: Excess shear stress, sediment and seawater densities, the Nikuradse roughness length.

Numerical Procedure: Hand calculations

Limitations: Steady flow conditions and wavy boundary.

Region Considered: Columbia River

Applicability to SAOS Region: Possibly during winter south of Cape Fear or during summer throughout the South Atlantic Bight, whenever steady conditions prevail.

Applicability to Other Regions: Widely applicable.

Cost to Run: Minimal

Error Estimate: Uncertainty of approximately 150 percent in output values.

2.4 A LITERATURE REVIEW OF WAVES, CURRENTS AND WAVE-CURRENT FORCES

2.4.1 Introduction

The design of offshore structures requires knowledge of the environmental forces which they will experience. Due to the exorbitant cost associated with failure of these structures and the high cost of construction, the need for accurate assessment of these forces or the statistics cannot be overemphasized.

The environmental forces offshore structures must be designed to resist are primarily forces due to winds, waves, currents, earthquakes, and ice (API 1976). This review includes only wave and current forces and is divided into the following three sections: waves (2.4.2), currents (2.4.3) and wave-current forces (2.4.4).

2.4.2 Waves

2.4.2.1 Wave Theories

Waves in the ocean often present a semblance of disorder. This is particularly true in the case of waves generated in severe storms which are highly nonlinear, directional and random. Confused as they may appear, however, these motions must satisfy basic laws of hydrodynamics. As has been the case with the history of all branches of sciences, the development of wave theory began with linear, undirectional and deterministic models. The first theory for water waves is that due to Airy (1845). The theory assumes that the fluid is incompressible, inviscid and the motion irrotational. Furthermore, the amplitude of the wave is small. To relax the assumption of small amplitude, Stokes (1847) extended the theory by a perturbation expansion on the amplitude. In recent years, the stream function wave theory developed by Dean (1965a, 1965b, and 1967) and Monkmeyer (1970) has been introduced to the profession. This theory proceeds through a direct numerical approximation to the solution of the governing equations. There have been many other nonlinear, unidirectional, deterministic wave theories developed (Kortweg and DeVries, 1895; Laitone, 1960; Scott-Russell, 1844;

Boussinesq, 1872; and McCowan, 1891), but they are either computationally more difficult, are more suited for regions other than offshore, or represent special geometric configurations not appropriate in most applications.

These classical wave theories have led to an understanding of the principal kinematical and kinetic relations of simple water waves whose appearance in nature, nevertheless, is found only in rare circumstances. When designing structures in the ocean, the chaotic nature of the sea must be taken into account. The method that promises a more realistic description of the sea is based on statistical time series analysis and probability theory. The applications of these methods in areas of water waves were pioneered by Darbyshire (1952), Longuet-Higgins (1952), Neumann (1952), Pierson (1952), and Putz (1952). In its simplest form, the statistical approach assumes that the sea is steady and spatially homogeneous. A concise exposition of this statistical model is given in Phillips (1977) and Borgman (1972). Attempts to take into account the nonlinearities of the sea surface were carried out by Longuet-Higgins (1963). Consideration of time and space changes have been made by Brown (1967) and Rosenblatt (1957). Analytical treatment of random waves is extremely difficult; the technique of simulation has been used to advantage, such as exemplified by the work of Forristall, et al. (1967).

2.4.2.2 Generation of Wind Waves

The selection of the ocean wave characteristics to be used in the design of an engineering structure ideally would be based on long term measurements of the waves occurring at the intended site. Such data is almost never available. In the absence of this information, two approaches may be used. In one, a short data base of wave measurements is directly extrapolated by curve fitting and the methods of extremal statistics to predict long term wave statistics. In the other approach, the available data is used to calibrate a physical model relating geostrophic winds (as determined from isobaric pressure maps) to waves which would be produced by that wind field. Then historic weather maps for 80 years or so are processed to predict the waves at the site during the past. This procedure has been called "hindcasting", since it is predicting the past, not the future. The hindcast procedures produce artificial wave data which can then be processed to predict the characteristics of the design wave. In essence, the short wave data base is augmented by long term meteorological data to produce more reliable predictions.

A very significant part of the physical model for wave hindcasting is a thorough understanding of the processes which produce waves. The first step toward an explanation of wind wave generation was taken a century ago by Helmholtz, who suggested a mechanism based on surface instability. His theory was later extended by Kelvin (1910) to include surface tension. The influence of viscosity was considered in the same physical model by Wuest (1949) and Lock (1954). The first distinct approach was that of Jeffreys (1926, 1928), often referred to as the sheltering mechanism.

The foregoing theories do not lead very far toward an understanding of the mechanism of wind wave generation because of the simple deception of the airflow which in nature is always turbulent. The first approach facing up to these characteristics is that of Echart (1953). In 1957, the picture radically changed with the introduction of two new hypotheses which are complementary to each other: the resonance hypothesis of Phillips (1957) and the shear flow hypothesis of Miles (1957). In Phillips theory, it is assumed that a random distribution of vertical wind gusts acts over the sea surface. The fluid is assumed to be inviscid and the fluctuations of air pressure are sufficiently small so that the generated waves are quasi-infinitesimal in height and no reverse coupling occurs. Miles followed the lead of Helmholtz, Kelvin and Jeffreys and considered that energy is transferred from wind to waves by pressure distributions related to wave form. The model, therefore, is a coupled one. Air turbulence, however, is introduced only insofar as it determines the average wind profile, but the airflow is laminar. Miles' and Phillips' models thus complement each other, but are not mutually exclusive. The resonance land shear flow models were combined by Miles (1960).

2.4.2.3 Wave Prediction

Verification of the Miles-Phillips mechanism has been compromised by the difficulty of making accurate wind speed and pressure measurements near waves.

However, the overall growth rates match results of field studies (Inoue, 1967; Bunting and Moskowitz, 1970; and Bunting 1970). Thus, most models of wave growth have used the equation for growth resulting from these mechanisms.

The first practical models of wind wave growth predicted only the total energy in the spectrum, or the significant wave height.

A quasi-empirical-quasi-theoretical procedure was earlier used by Sverdrup and Munk (1947) to construct the first widely used wave prediction system. This was later revised by Bretschneider (1952, 1958). Thus, this prediction system is often called the Sverdrup-Munk-Bretschneider method.

If the duration and fetch are large enough to permit an equilibrium state between the mean wind, turbulence, and the wave spectrum, all other variables are determined by the wind speed. The Pierson-Moskowitz spectrum (1964) is representative of such an approach. Other models include those given by Bretschneider (1959, 1963) and Roll and Fisher (1956). A more general model may be constructed by assuming that the sea is calm when the winds begins to blow. Integration of the equations governing wave growth then permit the consideration of changes in the shape of the spectrum with increasing fetch and duration. If enough wind and wave records are available, empirical data may be analyzed to provide similar information. Pierson, Neumann, and James (1955) introduced this type of wave prediction scheme based entirely on empirical data. Inoue (1966, 1967) repeated this exercise in a manner more consistent with the Miles-Phillips theory.

The most recent improvement of wind wave spectrum has been made in connection with extensive wave-growth studies under well defined wind conditions during the Joint North Sea Waves Project (JOHNSWAP). This is reported by Hasselmann, et al. (1973). A wave spectral model based on a parameterization of Hasselmann's wave-wave interaction theory has been constructed by Hasselmann, et al. (1971).

A model of the seaway suitable for describing the propagation of waves from a hurricane area was first introduced by Rosenblatt (1957) as mentioned earlier. In recent years, additional work was performed, the latest of which is represented by that of Kolpack (1977) and Cardone, et al. (1976).

2.4.2.4 Determination of Extreme Waves

When one is designing a structure to withstand wave action, it is important to estimate the highest waves to which the structure may be exposed. The ordinary statistics dealing with the properties of random data dispersed about a central value are not very helpful when one is essentially concerned with the behavior of values distantly located from the mean, as happens when seeking to predict the characteristics of extreme waves. To this end, one needs a set of statistical methods specifically designed to deal with the occurrence of rare events rather than with normal deviations.

Probability distributions of the extreme value of a variate have been studied by various mathematicians, notably Gumble (1958), who made the first compilation of the technique. Subsequently, the method was adopted for studies of extreme wind (1960) and extreme wave statistics (Ward, et al, 1978; Matushevskig, 1973; Borgman 1970, 1973 and 1975) for design considerations.

More recent work on the subject includes that of Forristall (1978), Herring, et al. (1976), Jahns and Wheeler (1973), and Ward, et al (1977).

2.4.3 Wave Current Interaction

If the site of a structure may come under the influence of current, the design of the structure must take into consideration the effects of current. Furthermore, if the wave and current are separately generated, then wave and current interact and wave characteristics undergo changes. For example, if current is in the direction of wave propogation then the wave amplitude decreases and its length increases, but if the current opposes the wave, then the wave steepens and shortens. An appreciation of offshore structure can be gained from Hogben (1974) and Wu and Tung (1975)

Currents occur in varied physical circumstances, some of them obviously not relevant to structure design. For example, the effects of current on capillary wave and small scale currents are of no concern in structural design. The type of currents that are considered are mainly those which are externally generated such as the Gulf Stream and those generated by wind. It is noted that in both cases the current speed and wave particle velocity may be of the same order of magnitude. Since fluid forces are proportional to the square of fluid velocity, an error of 50% under high wind conditions can easily occur if current is neglected.

In all water wave problems, approximations must be made to find mathematical solutions in order to gain physical understanding. Almost always, the water is assumed to be inviscid and the flow irrotational. The first assumption may or may not hold, depending on whether the current is uniformly distributed with depth. The following discussion is therefore divided according to these two cases.

2.4.3.1 Waves on Currents Uniformly Distributed with Depth

For horizontal currents that are slowly varying in time and nonhomogeneous in the horizontal space, but uniformly distributed with depth, the flow may be assumed to be irrotational. The methods commonly used for the solution are (a) the averaged Lagrangian developed by Whitham for nonlinear dispersive waves (Whitham, 1974), (b) the method of direct integration with respect to the vertical axis and averaging of the equations of motion (Phillips, 1977 and Hasselmann, 1971), and (c) the perturbation technique applied to the Laplace equation governing fluid motion and the corresponding boundary conditions (Longuet-Higgins and Stewart, 1960, 1961, and 1964). Various cases were considered including the cases in which the currents vary with distance along and/or across the stream.

Based on these theoretical considerations, the interactions of currents with random waves have also been studied (Phillips, 1970; Huang, et al., 1972; Tung and Huang, 1974; Gargett and Hughes, 1972; and Vincent). The influence of wave-current interactions on random wave forces and response of structures to random waves and currents was also investigated (Tung and Huang, 1973a and b, and 1974; Tung, 1974; Wu and Tung, 1975).

2.4.3.2 Waves on Currents Varying with Depth

Naturally occurring currents in moderately deep water usually vary with depth. When currents vary with depth, the flow is in general no longer irrotational. The common assumption of incompressibility is usually made and Coriolis force is neglected. Even with these assumptions, solutions for the two-dimensional case are difficult to achieve and simplifications based on physical considerations have to be introduced.

For infinitesimal waves, equations for variation of wave motion with depth have been solved for various simplified current profiles. For example, for stationary waves, analytical solutions may be found for a wide variety of velocity profiles. Peregrine and Smith (1975) gave a short table of solutions for various jet-like flows over still water. Lighthill (1953) and Fredsoe (1974) obtained solutions for specific classes of velocity profiles. Fenton (1973) gave a method that is appropriate when an analytic expression is available for the profile, but it may need modification if tabulated values of the profile are used. Many features of the equation of fluid motion with depth have been studied in connection with its singularity, critical layer and also upstream propagation by workers such as Craik (1968), Velthuizen and Van Wijngaarden (1969), Yih (1969 and 1972), and Benjamin (1957 and 1962).

When waves are of finite amplitide, the familiar method of expanding the free-surface boundary condition in a Taylor series about the mean level becomes inappropriate. If this approach is adopted, the mean flow must also be expanded in a Taylor series. While this may be sensible for a flow chosen for its mathematical convenience, such as a linear profile with constant vorticity, it is quite inappropriate if actual velocity measurements are used since even second derivatives may be quite uncertain. A number of transformations of the equations of motion for steady flow enables this problem to be avoided. Thus, for a two-dimensional flow in a gravity field, the equations of conservation of mass and momentum are replaced by a single equation in terms of the stream function. The equation is of course difficult to solve in general and a numerical method must be resorted to. Thus, Dalrymple (1973) presented a finite difference approximation to the equation for cases of linear and one-seventh power velocity shear profiles. Dalrymple (1974) extended these results by assuming more general velocity profiles. Finally an approximate solution to the vorticity equation for the case of finite amplitude random waves was suggested by Rupert (1976), but no further application to wave-current forces has been indicated in the literature.

2.4.4 Wave-Current Forces

From the standpoint of design of offshore facilities, the utlimate purpose of studies of waves and currents is to enable one to compute wave and current forces on these structures. The manner in which fluid forces on objects are computed depends on whether the object is "small" or "large" compared with "dimensions" of the wave. Thus, piles and members of an offshore tower are considered small objects and oil storage tanks and deep water docks are large bodies in the literature of fluid force studies. The reason that such distinctions are made can be seen if one recognizes that when the body dimension is small compared with wave amplitude, flow separation and energy dissipation in eddy formation become important. Furthermore, when the lateral dimension of the body is much less than the wave length, the wave field is not greatly disturbed. However, as the lateral dimension of the body increases to become comparable to the wave length, the presence of the body begins to alter the wave field. When such interference is appreciable, wave scattering, or diffraction must be considered. In the following, forces on small and large bodies are discussed separately.

2.4.4.1 Forces on Small Bodies

As early as 1851, Stokes undertook to study the motion of pendulums in an unlimited viscous fluid in which he indicated that the force to which the pendulum is subjected consists of two terms: one involving velocity, the other, acceleration of the pendulum. Subsequent to Stokes' work, Basset (1888) studied the forces on a sphere moving in a viscous fluid in an arbitrary manner, and Rayleigh (1911) studied the same for a more restricted type of motion. When the Reynolds number is large and the flow turbulent, a theoretical analysis of the problem is difficult and much of the desired information must be obtained experimentally. To offer an indication of the degree of difficulty of the problem, the physics underlying the flow around a body is given below.

When an inviscid fluid is accelerated past a stationary object, the object experiences a resistance which is equal to the sum of the pressure components, around the body, in the direction of acceleration. Part of this inertial force is derived from the pressure gradient to accelerate the ambient flow; the remainder accounts for the resistance resulting from the acceleration of the fluid particles induced by the body, as would be the case of the body were accelerated through an inviscid fluid at rest.

When a viscous fluid is accelerated past a stationary object, the motion which starts from rest is initially irrotational and unseparated. As the velocity increases, a wake forms and grows. The formation of the wake gives rise to not only a form drag, as would be the case if the motion were steady, but also to significant changes in inertial forces. The effects of unsteadiness depends on the intensity and duration of the acceleration, the time required for the formation of a wake, and upon the degree to which the body is streamlined. The velocity-dependent form drag is not the same as for steady flow of a viscous fluid and the acceleration-dependent inertial resistance is not the same as for unsteady flow of an inviscid fluid. The drag and inertial forces are interdependent as well as time dependent and dependent upon the preceding history of the fluid motion.

For unseparated flow, the coefficients appearing in the drag and inertial terms have been determined for a wide range of body shapes partly theoretically, and to a large extent experimentally (Sarpkaya, 1960). The coefficients obtained for unseparated, unsteady flows are, however, not applicable to occurrences in which the duraion of flow is long enough, and the body form blunt enough for separation to occur.

At the University of California, a series of studies were conducted in which various bodies were accelerated undirectionally (Iverson and Balent, 1951; Morrison, et al, 1953; Laird, et al, 1959; and Laird and Johnson, 1956). The results are expressed in terms of a total resistance coefficient in which the effects attributable to both velocity and acceleration are necessarily superimposed. Keulegan and Carpenter (1956), using periodic waves, were able to separate the total resistance into drag and inertial components. Following the works cited above, the determination of drag and inertial coefficients has become the subject of many theoretical and experimental studies in the ensuing years

(McNown and Wolf, 1956; Kulin, 1958; McNown and Keulegan, 1959; Bryson, 1959; McNown and Sarpkaya, 1960; Sarpkaya and Garrison, 1963; Sarpkaya, 1968; Jen, 1968; Heinzen and Dalton, 1969; Hamann and Dalton, 1971; Sarpkaya, 1975; and Sarpkaya, 1976), the more comprehensive laboratory investigation on the subject to date being that due to Sarpkaya (1976).

In spite of the excellent results obtained in the laboratory experiments, it is noted that the usually large dissimilarity between the key parameters in the laboratory and in nature, makes direct application of laboratory results to the field questionable and field experiments must be carried out.

The number of field programs that have been conducted, and the results obtained is fairly limited. Two of the most extensively studied field programs to measure waves and wave forces are the so-called "Wave Project I" and "Wave Project II." Wave Project I was conducted in approximately 10 metres of water depth and consisted of four instrumented pilings and three wave staffs. Wave Project II was installed in 1960 in a water depth of 30 metres, and consisted of a single wave staff and eight "clamp-on" dynamometers distributed along a single instrument piling. Major efforts to analyze these data are given by Evans (1969), Wheeler (1969), and Dean and Aagaard (1970). In these projects, water particle velocities were not measured. In order to determine the drag and inertial coefficients, wave kinematics must be inferred from wave profiles as predicted and selected wave theories. The scatter in the resulting coefficients is substantial and it is clear that a significant, but somewhat unquantitied, portion of this scatter is due to the fact that there are considerable differences in the kinematics predicted by various wave theories

Within the last decade, field measurement of water particle kinematics has become possible largely through the development of the electromagnetic current meters and also possibly through use of high-response duct current meters. Recently, a group of petroleum companies launched the "Ocean Test Structure" project, a jointly sponsored large-scale engineering experiment designed to help establish the actual values of wave forces. The structure was fabricated, calibrated and installed in 1976 in the Gulf of Mexico (Loftin and Pearce, 1975). In addition to the extensive wave force data collected, wave profile and wave kinematics were simultaneously obtained. This enables one to verify the various wave theories and makes the evaluation of the force coefficients more meaningful.

It is well known that in nature, waves can only be described in a probabilistic sense. This has made the determination of the force coefficient doubly difficult. First of all, there is added difficulty in the task of verification of the wave theories. Secondly, methods must be developed for the determination of the force coefficients, which in turn requires the development of probabilistic methods of wave force calculation. Probabilistic description of wave forces in a random sea was first studied by Pierson and Holmes (1975) and Borgman (1965, 1966, 1967 and 1972). Methods for the estimation of force coefficients were pursued by Brown and Borgman (1967) as summarized by Borgman (1972) and later, by Dean (1976). In addition to the above works, the problem of the effects of free-surface fluctuations on wave field, wave force and wave force coefficients was studied by Reid (1958), Wheeler (1970), Tung (1975a and b), Pajouhi and Tung (1975), Tung and Pajouhi (1976), and Tung and Brooks (1979).

In the above discussion, no mention is made of the effects of current. Since the force coefficients are influenced by the wake and the presence of current advects the residual wake away from the object, an experimental program similar to the work of Sarpkaya must be carried out before the effects of this wake removal on force coefficients can be assessed. The problem of wave-current force is further complicated by the uncertainty introduced into the "wave" theories now affected by the presence of current; the influence of current on waves and wave field kinematics has not been entirely solved in the case when current is varying with depth. For the cases in which current is uniformly distributed with depth and waves random, however, probabilistic framework for wave-current force computation has been developed for both the cases in which free surface fluctuations are ignored (Borgman, 1967), and included (Tung and Huang, 1973a and b).

2.4.3.2 Forces on Large Bodies

When considering ocean structures whose lateral dimensions are large compared with wave length, separation is negligible, but scattering is the main feature. Such a problem is mathematically well-posed and lends itself well to mathematical treatment. Nevertheless, theories have only been developed for linear waves and most of the studies have been restricted to the linearized potential theory. As such, for stationary bodies, the effects of steady current are static in nature and can be treated separately and superposed on the solution due to waves.

Exact solutions of the linearized boundary value problems have been achieved only in a few instances; they are, vertical circular cylinders (McCamey and Fuchs, 1954), semi-infinite breakwaters of zero thickness (Heins, 1948), thin vertical plate beneath the free surface (Dean, 1945), or piercing the free surface (Ursell, 1949), and inclined surface piercing plate (John, 1948).

For bodies of simple geometry such as rectangular cylinders in the free surface or horizontal submerged cylinders and docks or storage tanks which are circular symmetry about a vertical axis, a semi-analytical theory has been developed (Garrett, 1971; Mei and Black, 1969; and Black, et al, 1971). These structures, however, must have vertical side walls and horizontal bottoms.

For more general geometries in two and three dimensions, there are two powerful numerical methods: (a) the integral-equation method and (b) the hybrid-element method.

The method of integral equations begins with a singular solution such as a Green's function that satisfies the governing equations and nearly all the boundary conditions except that on the body surface. Applying the boundary condition on the body, an integral equation can be obtained. Only in a few exceptional cases can the integral equation be solved exactly. The advent of large computers now makes it possible to discretize the surface of the body so as to replace the integral equation by a finite number of algebraic equations. The application of the integral-equation method to wave force computations has been made by C. J. Garrison and Seetharama Rao (1971), Bai and Yeung (1974), Yeung (1975) and Black (1975).

The second major class of methods that has been rapidly developing into a powerful alternative to the integral-equation method is the finite element method, which has scored spectacular successes in structural mechanics (Garrison and Rao, 1971; and Hueber, 1975). A succinct survey of the application of the finite element method to fluid mechanics problems is given by Shen (1977).

The finite element method applied to a linear boundary value problem involves the following few key steps: (a) express the boundary value problem variational principle where a certain functional is stationary; (b) discretize the region into finite elements; (c) select interpolation functions that approximate the solution inside the finite elements. The interpolation functions involve unknown coefficients; (d) for each element, perform the differentiations and integrations in order to express the functional as a bilinear form for the unknown coefficients; (e) assemble the element bilinear forms so that the total functional is expressed as a global bilinear form; (f) extremize the functional with respect to each unknown coefficient and obtain a set of linear algebraic equations for the coefficients.

The scheme described above is quite adequate for most structural mechanics problems of bounded domain. For water wave problems which involve unbounded domains, direct application of the finite element method requires the use of large numbers of elements and hence the solution of large systems of algebraic equations. To reduce the computing cost, the hybrid-element method was introduced. The method takes advantage of the fact that analytical solutions for the far field are usually known. Thus, if the body of water is divided into two parts, and the solution to the governing equation for the far field is expressed in terms of unknown coefficients of the series solution and the inner region is treated by the finite element method, a set of algebraic equations can be established by enforcing continuity at the interface of the two regions; the size of the equation can thus be greatly reduced.

Application of the hybrid element method to wave and wave force problems was first attempted by Berkoff (1972) in studying the diffraction of waves by an island. Subsequently, Chen and Mei (1974) and Bai and Yeung (1974) used this approach for two dimensional scattering and radiation problems. The three-dimensional scattering problems were studied by Yue, et al, (1976). The work of Chen and Mei was motivated by the need for the solution for the proposed offshore harbor for a floating nuclear power plant near Atlantic City, New Jersey. The same program has been modified for variable depth by Houston (1976) who has made extensive applications to study Port Hueneme, Los Angeles Harbor, and Long Beach Harbor for the design of piers and terminals.

In conclusion, it is revealed that although these general methods are now available for the solution of water wave problems, many wave problems remain to be studied. For example, in reality, the sea in a severe storm is random and of large amplitide. These two factors alone pose severe difficulties in the solution of the boundary value problem. Methods of solution to this nonlinear random boundary value problem are important items for further research which are in the area of state-of-the-art of research efforts.

3.0 QUANTITATIVE MODEL EVALUATION

3.1 BACKGROUND

It was originally intended as part of this evaluation effort to be able to do some actual quantitative estimates of model skill for those models that were deemed most likely to provide the desired products to BLM. Several factors constrained the degree to which that level of evaluation could be applied. First, there was the unavailability of computer code for those models; second, there was the constraint of not being permitted to actually run any models under this contract; third, there was the unavailability of actual model results and field verification values. The only models for which all of this information was available and for which we did not have to use any computer time were the Hsueh and Peng (1978), and Hsueh and Lee (1978) diagnostic models which were reported in the BLM model evaluation workshop. What is discussed herein are the same data with additional explanation which should provide the tools for doing quantitative evaluations in the next phase of BLM model development and application, and should serve as an example of how a quantitative analysis of model output should be done.

Also, in the last part of this Section (3.3), we have briefly summarized published results of comparisons of model runs and actual field data for three of the models evaluated in Section 2.2 of this report: Simons (1975), Bennett (1977), and Hamilton and Rattray (1978). These are the only models (of those evaluated) for which such comparisons are available.

3.2 QUANTITATIVE MODEL EVALUATION TECHNIQUES AND EXAMPLE

Experience from developing both steady-state and time-dependent models for bottom currents in New York Bight indicates that steady-state models used in an episode-oriented mode are capable of producing mean current patterns that are qualitatively similar to those observed and averaged over the duration of the episode that lasts typically for a week or more (See Figure 3-1). Since the mean current on the open continental shelf is generally an order of magnitude smaller than the fluctuations, it is far more significant to note that observed currents at subtidal frequencies are quite readily simulated also by long wave models (See Figure 3-2). Forward scattering of long waves incident upon topographic features such as the Hudson Canyon in New York Bight does not seem to have much ramification except perhaps immediately downstream from these features.

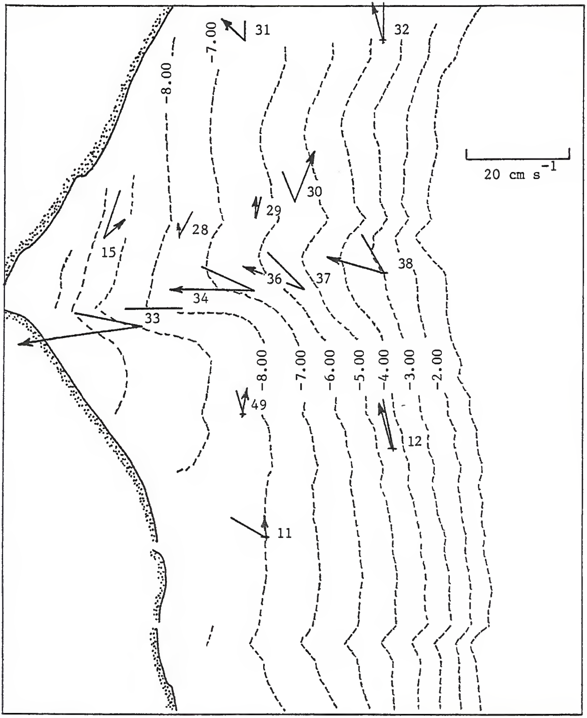
In terms of model verifiation, the use of linear regression techniques, skill computation, absolute error estimation, and the standard coherency analyses appears to provide an adequate objective assessment, the results of which can be used to determine suitability of models for the purposes intended by BLM.

3.2.1 Relative Error (Skill Computation)

The relative error (R_o) is a measurement of model skill which is motivated by the need to gain a feel for the certainty with which deep residual currents may be estimated form bottom velocities monitored along a single cross-shelf transect. It is biased against small differences; on the other hand, for the same R_{comp}, model skill can appear high purely because observed difference is large. It is thus important to complement the R_o computation with an estimate of the absolute error (R_A) of the velocity field of the model which will be discussed in the next section.

$$R_o = \left[\frac{(R_{obs} - R_{comp})}{R_{obs}}\right] \times 100$$

$$= \frac{\int (v'_2 - v'_1)^2_{obs}\,dt - \int (v'_{2obs} - v'_{2comp})^2\,dt}{\int (v'_2 - v'_1)\,^2_{obs}\,dt} \times 100$$



Near-bottom, mean current vectors for episode Julian day 90-95 (March 31 - April 5). Observed vector shown as heavy line with arrowhead; model results as light line. Also shown are isopleths of bottom pressure, in units of sea-surface elevation (cm). (In the model, pressure is fixed at zero along the offshore boundary; the velocity vector is assumed not to veer in a bottom boundary layer of 5-m thickness; and the observed alongshore flow at moorings P31 and P32 is used as the upstream boundary condition.)

Figure 3-1. Comparison of calculated and measured mean current vectors

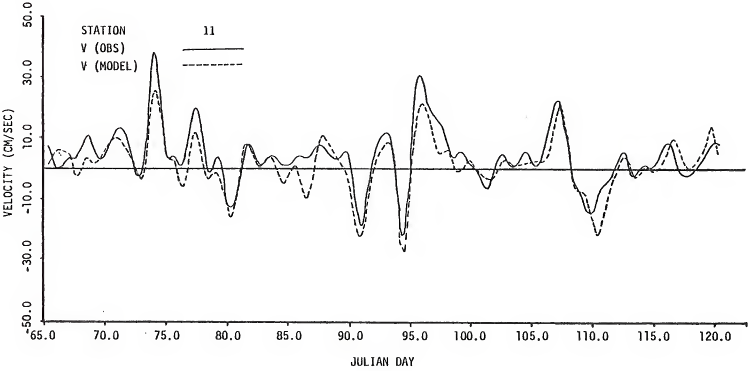


Figure 3-2. Comparison of Time-Series of Bottom Currents Derived by Model and Actually Observed

where R_0 = percentage variance of the model, R_{obs} = squared difference between observed velocities at two different points, and R_{comp} = squared difference between computed and observed velocities at a point where model prediction is made. R_0 will vary from zero to negative infinity with zero representing a total agreement between the observations and model computations and negative infinity representing no fit of the data. This criterion utilizes phase information as well as amplitude.

3.2.2 Absolute Error (R_A)

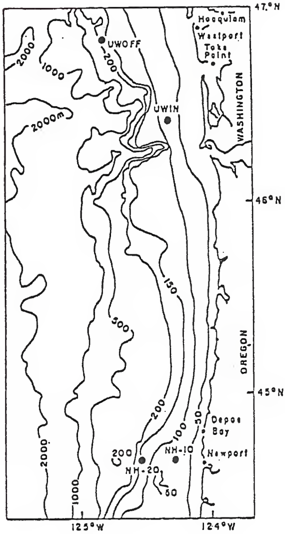
It is important to complement the R_0 computation with an estimate of the absolute error of the model velocity field. For a measure of the absolute error, we compute the ratio of R_{comp} to the square of the observed velocities and name the ratio R_A. So the smaller the value of R_A, the better are the model results in the absolute sense.

$$R_A = \frac{R_{comp}}{V^2_{obs}} = \frac{\int (v'_{2obs} - v'_{2comp})\ 2dt}{\int v'_{obs}\ 2\ dt}$$

where R_A represents the root mean square error expressed in the units of the computed variable, e.g., cm.x^{-1} for velocity. Examples of absolute error values are shown in Figure 3-3 (numbers in parentheses) for a case study involving comparison of current velocities obtained from two moorings along the Oregon-Washington Continental Shelf.

3.2.3 Standard Coherency Analysis

Diagnostic/predictive models have discernable frequency distributions of both coherency and phase, as illustrated in Figure 3-4. Phenomena over certain frequency ranges will be modeled better than those over other frequency bands -- this being related directly to the extraneous noise of the natural system, numerical noise, the degree of non-linearity of the system, and the applicability of the model to the physical processes which themselves have distinct frequency distributions. Coupling the coherency/phase estimates with the frequency distribution of variance will determine the processes which can be adequately modeled and the relative and/or absolute errors in modeling these processes. By employing a



		Inviscid Model	Viscous Models		
			δ=10m	δ=20m	δ=30m
DB-7	u	-83(32)	40(3)	80(1)	80(1)
	v	-63(*)	82(49)	97(6)	99(0)
POL	u	0(18)	58(12)	58(12)	75(4)
	v	81(*)	95(*)	97(*)	99(11)

*over 400%

NOTE: Percentage of explained variance along the 100 m isobath (R_A) values in parentheses.

Figure 3-3 Example of Absolute Error

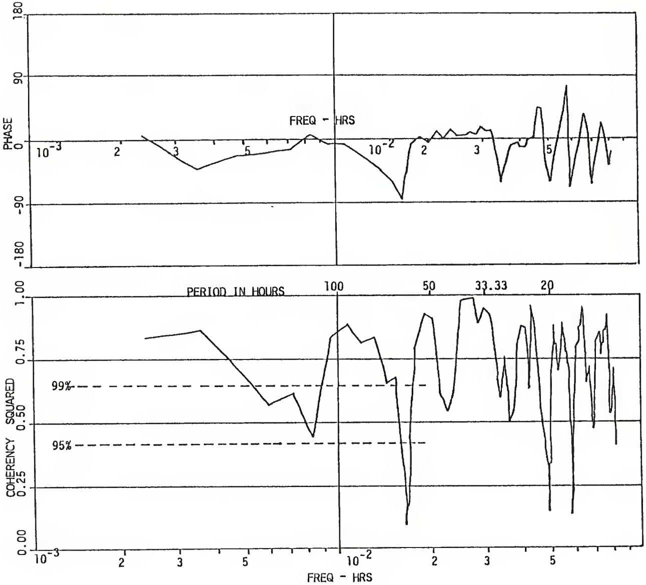


Figure 3-4 Example of Frequency Distributions of Diagnostic/Predictive Models in Phase and Coherency

transfer function analysis, the time series resulting from the model calculation can be compared directly to: a) the observed time series, and b) the linear least square error time series obtained from the model input data and the observed variables. This will provide the clearest visual display of just how well the observations and the model results are related to the system inputs.

3.2.4 Linear Regression Techniques

The distribution of errors criterion addresses the reliability of models in terms of temporal and spatial scales. The effectiveness with which it may be applied depends on the extensiveness of the relevant data base and the extent of detectable variance in the distribution of properties. Worthy models must yield results that are reasonably coherent with observations at the scales of importance. For example, in oil/toxicity distribution prediction, since it is the first three or four days after an oil spill that are really important on the basis of the fact that surface water moves with three percent of the wind, models must yield concentrations that are reasonably coherent with observations at, say, spatial scales of 3 kilometres or less for a wind speed of $14 ms^{-1}$ (30k) or so.

3.3 COMPARISONS OF MODEL COMPUTATIONS AND FIELD OBSERVATIONS REPORTED IN THE LITERATURE

Of the more than twenty water column models examined in detail in Section 2.2.2 of this report, only three, beyond the Hsueh-Peng (1978) and Hsueh-Lee (1978) models, reported comparison of model output with actual field measurements: Simons (1975), Bennett (1977), and Hamilton and Rattray (1978). None of these three involves a quantitative or statistical comparison of model computations and field observations as described in the previous sections; although two of these comparisons (the first two cited above) are fairly extensive, they are all qualitative. These summaries are provided as examples of the types of model computation-field data comparisons that are usually undertaken.

3.3.1 Simons' (1975) Model of Lake Ontario

The entire Simons (1975) paper is devoted to verification of a numerical model for Lake Ontario and is one of three papers written by him on the topic. Emphasis is placed on circulation during the month of August when the lake is strongly stratified. He also makes comparisons of thermal structure, heat balance, heat flux, and water levels. Comparison of currents is based on filtered time series data in order to allow evaluation of model performance in various frequency bands. Time scales are on the order of a few days so that currents can be averaged over four inertial tidal cycles.

Simons found that for time scales greater than the interial period there was fairly good agreement between model computations and field observations. There were serious limitations imposed by the spatial scale of the model. There was general agreement between computed and observed water levels and heat balance, but temperature predictions (thermal structure) were only in agreement with large scale patterns resulting from advection. The model was unable to simulate the growth and decay of the thermocline. Simons concluded that "A multi-layer hydrodynamical model . . . is capable of computing the transport characteristics of large natural basins to the extend required by water quality models. "He does not specify the degree of skill for his model, nor does he specify the input requirements for the water quality models mentioned in the text.

3.3.2 Bennett's (1977) Model of Lake Ontario

Like the Simons paper discussed above, the Bennett (1977) paper provides an extensive comparison of model predictions and field observations. However, it too is a qualitative comparison looking at the gross features of lake circulation. Bennett concentrates on the dynamic heights and currents at 14m depth, emphasizing the months of July and August when Lake Ontario is strongly stratified. His field data were provided by a lake-wide current meter array.

Bennett is quite critical of the model and cites two major indications of inadequacy. First, although the model predicted the correct monthly mean eastward component of flow over most of the lake, it does show a broad band of eastward flow along the north shore in the direction of the wind which is directly opposite to the observed currents. According to Bennett, there is no evidence of flow as predicted by the model in any of the data. Also, the model predicts a mean upwelling of the thermocline accompanying this eastward flow, when actually there is a "down-tilt" of the thermocline and a westward flow along the north shore. The second inadequacy was in the model's ability to reproduce the observed strength of current reversals and changes in the thermocline depth. Bennett speculates that lowering friction and resolving the coastal zone would improve model computations.

The final analysis made by Bennett involves the comparison of two cases of the model with two different friction formulations (A=4 and A=32, where A is viscosity). He compares the simulated time averaged flow from these two cases with observed eastward current velocity at 14m depth. Figure 3-5a gives a visual comparison of the results.

3.3.3 Hamilton and Rattray's (1978) Model of Upwelling on a Continental Shelf

The Hamilton-Rattray (1978) continental shelf upwelling model is compared to a region of known upwelling off the coast of northwest Africa. The authors acknowledge that this does not represent a detailed simulation since there was no attempt made to tune the model to available data. According to the comparison provided, the model results give a qualitative representation of the data which is suitable for interpretation of the observations of a nine day wind event. It should be noted that this was the only model comparison which attempted to quantify, even in a crude manner, the model skill.

Results of the comparison of measured and computed longshore (u) and offshore (v) velocity profiles for 31 March are shown in Figure 3-5b. The authors state that longshore velocity is approximately 15% higher than the measured velocity and the measured shear in v, near the surface, is greater than the computed value. A crude visual comparison of the offshore component shows errors ranging up to near 90% at depths of approximately 14m.

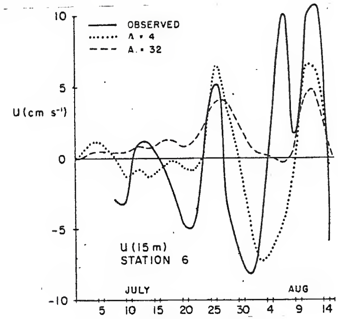


Figure 3-5a. Comparison of eastward current velocity components at 15m depth approximately 10 km south of Oshawa (solid line) with computed values using vertical eddy viscosity of 4(dotted line) and 32(dashed line). Taken from Bennett (1977), Figure 10.

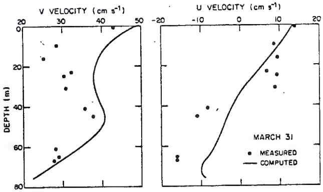


Figure 3-5b. Comparison of u and v velocity profiles (solid lines) generated by the upwelling model with current meter data (dots) after four days of wind. Taken from Hamilton and Rattray (1978), Figure 19.

The papers goes on to say that although there are discrepancies between the magnitudes of measured and computed currents, the model is able to reproduce, "in a qualitative sense" (our emphasis), the observed currents at a midshelf site during an upwelling event. The model was unable to reproduce the density field in the spindown situation which, in the opinion of the authors, was due to "local effects resulting in rapid restratification due to local advection of less dense water or to rapid heat flux through the surface."

4.0 ASSESSMENT OF ADEQUACY OF DATA BASE

4.1 HYDROGRAPHY

For diagnostic models, such as those recommended in this report, the primary variable field necessary for boundary and initial condition specification is the density field. When the density is specified at all points in the model numerical grid according to specific observations, the points in the model numerical grid according to specific observations, the velocity field consistent with the imposed dynamical constraints is allowed to spin up from rest. Even for a predictive model, initialization with an observed mean density field is effective in reducing the transient spin-up time considerably, since the baroclinic adjustment time for the mass field is on the order of a thousand years. In practice, density values of the necessary precision must be calculated from measurements of temperature, salinity, and pressure. The archiving of such hydrographic data is a function of the National Oceanographic Data Center (NODC), and the existing data base used for model input here is defined as that presently on file at the NODC.

Basically, NODC maintains four discrete types of data files based on the data acquisition sampling system. These files are classed as mechanical bathythermograph (MBT), expendable bathythermograph (XBT), bottle cast (station), and electronic salinity, temperature, depth sensors (STD). Table 4-1 gives the nominal overall accuracies for these data. Williams, Godshall, and Rasmusson (1977) have compared data from the different files in detail, and have reached the following summary conclusions. Large differences are observed in mean temperature profiles of MBT, XBT, and station data. Visual comparisons of profiles, frequency distributions, and application of hypothesis test suggest that significant differences in the means of these data sets exist. Although a significant difference in

Instrument	Variable Measured	Nominal Accuracy*	Notes
Mechanical Bathythermograph (MBT)	Temperature (T)	±0.5°C and ±3 m.	Accuracy highly dependent on particular calibration methods and care of users.
Expendable Bathythermograph (XBT)	Temperature (T)	±0.1°C and ±-2 m.	Repeatability of the digitized XBT record is ± 0.02°C and ±2 m.
Bottle Cast	Temperature (T) Salinity (S) Oxygen (O_2) Nitrate (NO_3) Phosphate (PO_4) Silicate (SiO_3)	T: ±0.02°C S: ±0.02°/oo O_2: ±0/04 ml 1^{-1} NO_3: ±5% PO_4: ±10% SiO_3: ±8%	NODC does not distinguish between temperatures and salinities from bottle casts or from STD sensors.
Electronic Temperature,	T: ±0.02°C		
Salinity, Depth Sensor	S: ±0.03°/oo		

*Accuracies approximate; a function of the manufacturer.

TABLE 4-1. SPECIFICATIONS FOR OCEANOGRAPHIC DATA TYPES AVAILABLE AT NODC

these bases has not been conclusively established, major differences have been shown to exist in mean profile magnitudes and shapes and in standard deviations. Whether these data sets can be combined without adjusting for relative biases is questionable, and until a more comprehensive MBT, XBT, station data comparative analysis is made, the data bases should be analyzed separately.

Within any given file, a further source of error for an individual station profile may be internal wave induced bias. The magnitude of this error is a function of the vertical gradient in the particular variable, winch speed, sensor response, time, as well as of the wave properties themselves. It is neither feasible nor necessary to evaluate this error for a particular profile, since the model inputs are statistical in nature and such biases should cancel in the mean, provided that the sample size is sufficiently large (typically greater than 10). Caution should therefore be exercised during initial spin-up where the data density is particularly low. In any case, a sufficiently long model run will ultimately eliminate any such relatively small residual biases.

Figures 4-1 through 4-4 show, over the domain of the SAB region, the spatial densities of station, XBT, MBT, and STD observations, respectively, each integrated on a seasonal basis. Seasons are defined as follows: winter, January through March; spring, April through June; summer, July through September; fall, October through December. The spatial resolution, or class interval size, for sorting observations is a one-degree (latitude and longitude) square for station, XBT, and MBT data, and a ten-degree (or Marsden) square for STD data. These choices were dictated solely by the inventory output formats available from NODC. In particular, a comprehensive and detailed STD data inventory of existing archived data is not presently available. The observations reflected in Figure 4-4 were hand culled from a variety of listings and file indices, and represent a coarse estimate of the actual data distribution. Since it is reasonable to assume that most future hydrographic data will be of the STD type, present deficiencies in archiving techniques need to be eliminated as a prerequisite to tests of statistics, such as stationarity.

For a given season, the distribution of data over the years (1900 to 1977 for station, XBT, MBT data; 1900 to 1978 for STD data) is not uniform. The stationarity of a particular seasonal average is a function of space (three-dimen-

Number of Observations

	None
░	1 to 10
○	11 to 40
▒	41 to 70
▓	71 to 100
█	more than 100

Key to Figures 4-1 through 4-4

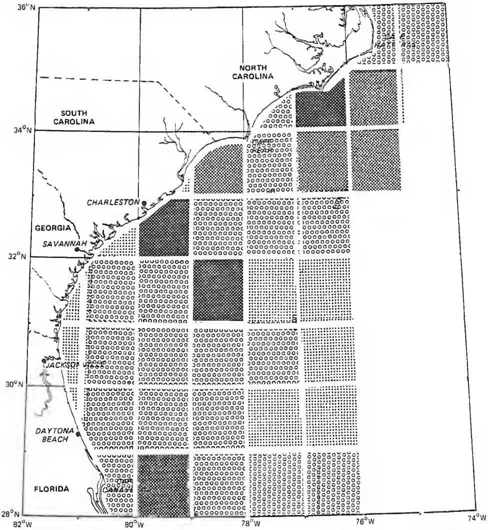


Figure 4-1A Hydrographic Station Data Density for Winter

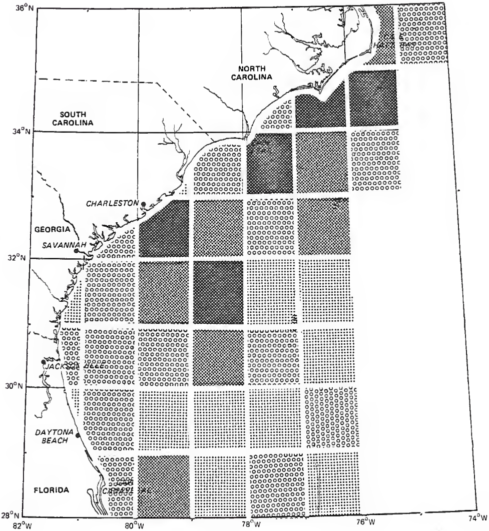


Figure 4-1B Hydrographic Station Data Density for Spring

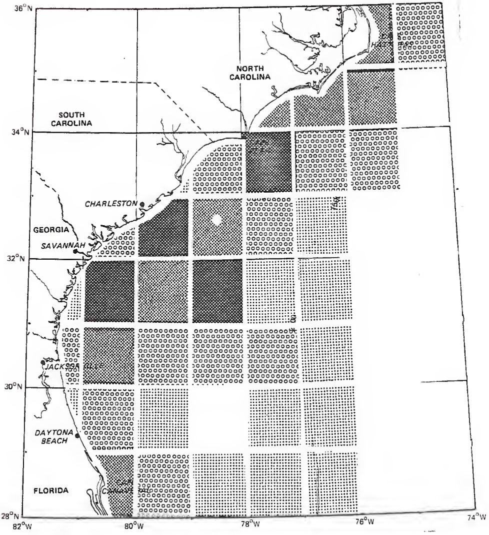


Figure 4-1C Hydrographic Station Data Density for Summer

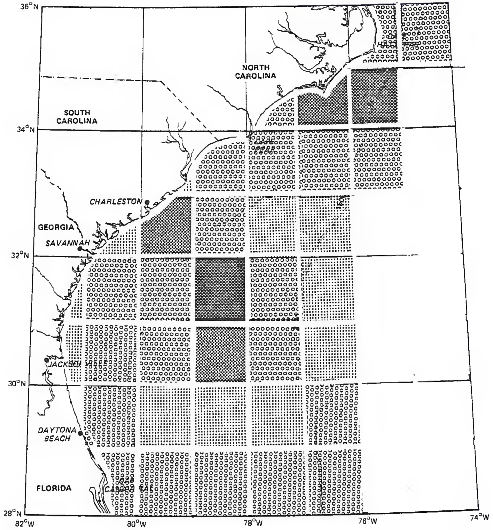


Figure 4-1D Hydrographic Station Data Density for Fall

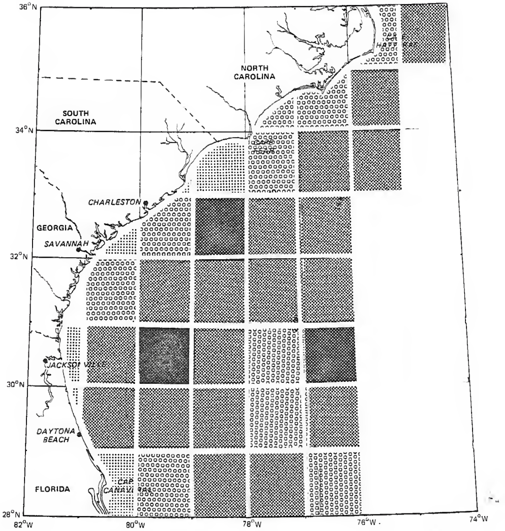


Figure 4-2A Expendable Bathythermograph Data Density for Winter

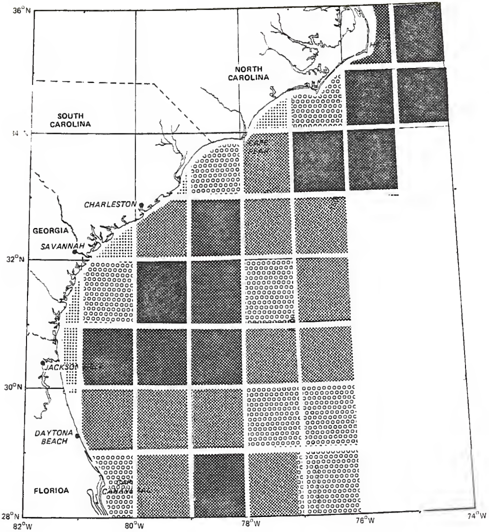


Figure 4-2B Expendable Bathythermograph Data Density for Spring

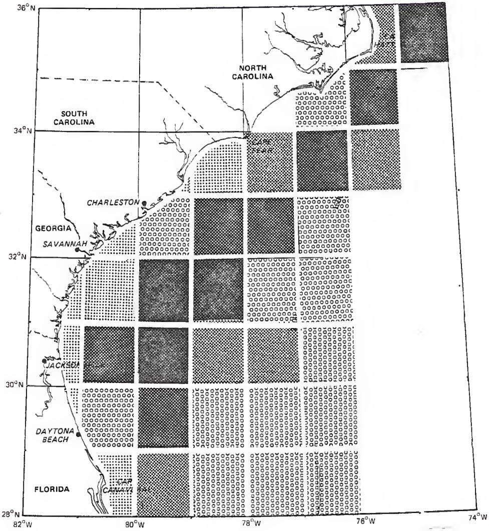


Figure 4-2C Expendable Bathythermograph Data Density for Summer

IN REPLY REFER TO
1120 (400)

United States Department of the Interior

BUREAU OF LAND MANAGEMENT

NEW ORLEANS OUTER CONTINENTAL SHELF OFFICE
HALE BOGGS FEDERAL BUILDING
500 CAMP STREET—SUITE 841
NEW ORLEANS, LA. 70130

Gentlemen:

Enclosed is a copy of a final report submitted to the Bureau of Land Management, New Orleans OCS Office, in conjunction with the Bureau's Outer Continental Shelf (OCS) Environmental Studies Program.

The Outer Continental Shelf Environmental Studies Program has been established by the Bureau to provide information about the OCS environment that will enable the Department of the Interior and the Bureau to make sound managerial decisions regarding the development of mineral resources on the Federal OCS; to acquire information which will enable BLM to answer questions about the impact of oil and gas exploration and development on the marine environment; to establish a basis for prediction of impact of OCS oil and gas activities in frontier leasing area; and to acquire impact data that may result in modification of leasing stipulations and OCS operating orders, notices, and guidelines, permitting efficient resource recovery along with environmental protection.

Studies conducted for the OCS Environmental Studies Program include literature surveys and syntheses; major environmental baseline and monitoring studies (chemical, biological, geological, and physical characterizations of frontier leasing areas); and special studies (site-specific environmental studies, or topic-specific laboratory studies in support of the environmental studies). Final reports submitted to the Bureau in partial fulfillment of the contracts under which these studies are performed are generally comprehensive technical/scientific reports or literature surveys.

These reports are available only in very limited numbers; to facilitate distribution and accessability to state and Federal employees, and to interested private citizens, the New Orleans OCS Office has established a formal distribution for reports submitted for studies conducted in the Gulf of Mexico and southern U.S. Atlantic Coast. A listing and status of all such reports received to date is attached.

If you have any questions concerning the studies program in general, or the availability of any studies program reports, do not hesitate to contact Dr. E. D. Wood or Dr. Richard Defenbaugh of the New Orleans OCS Office. Please contact us if you do not wish to continue receiving these reports.

Sincerely,

John L. Rankin
Manager

attachment

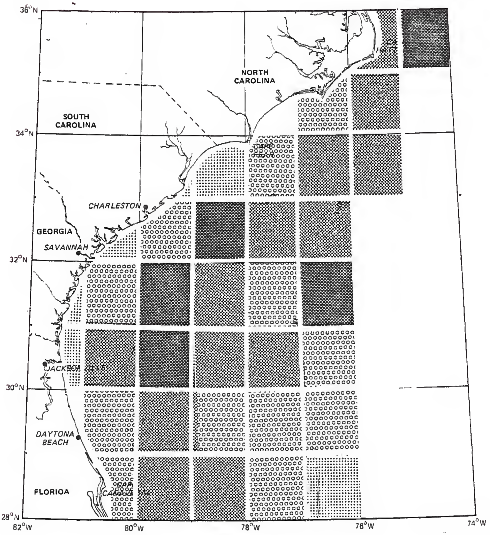


Figure 4-2D Expendable Bathythermograph Data Density for Fall

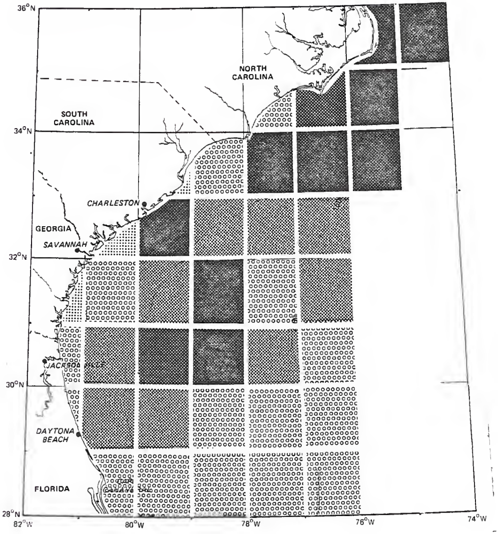


Figure 4-3A Mechanical Bathythermograph Data Density for Winter

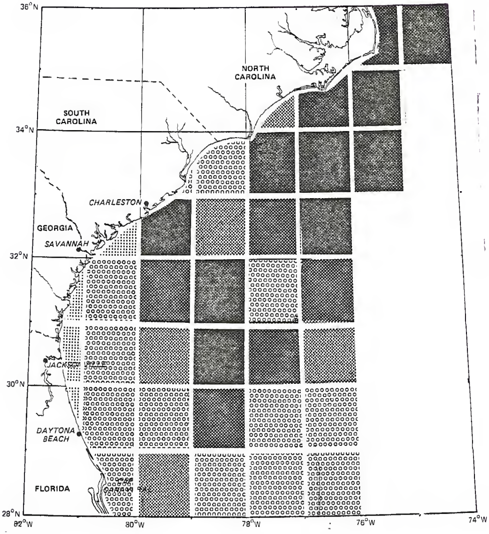


Figure 4-3B Mechanical Bathythermograph Data Density for Spring

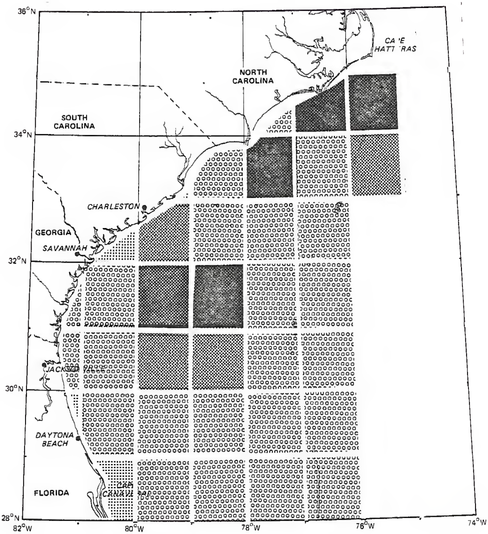


Figure 4-3C Mechanical Bathythermograph Data Density for Summer

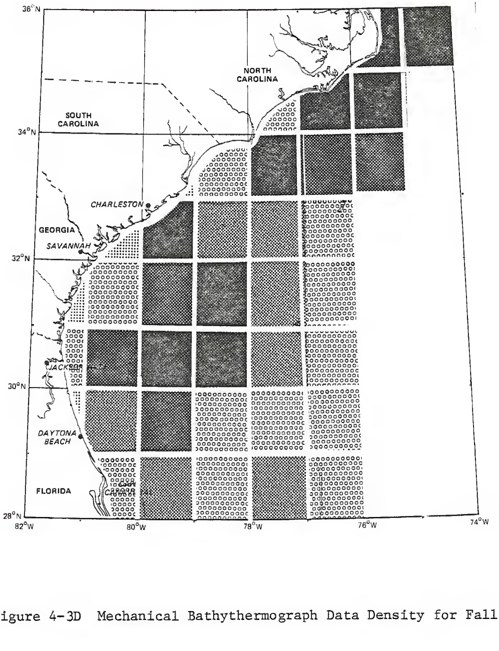


Figure 4-3D Mechanical Bathythermograph Data Density for Fall

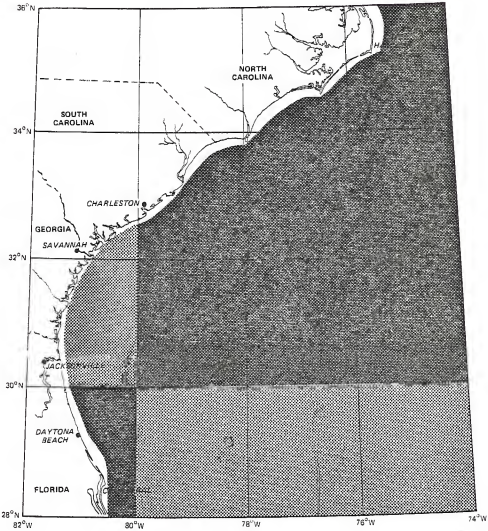


Figure 4-4A STD/CTD Station Data Density for Winter

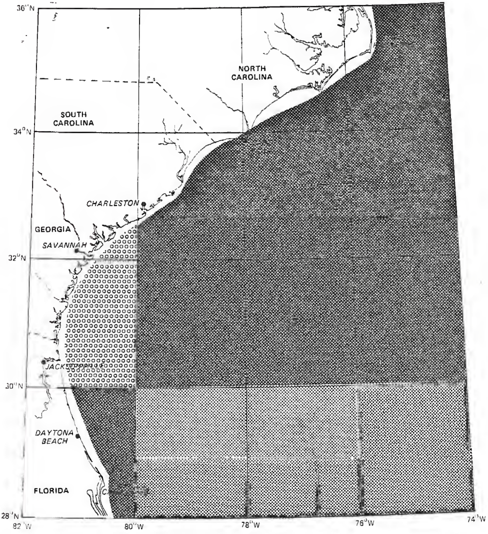


Figure 4-4B STD/CTD Station Data Density for Spring

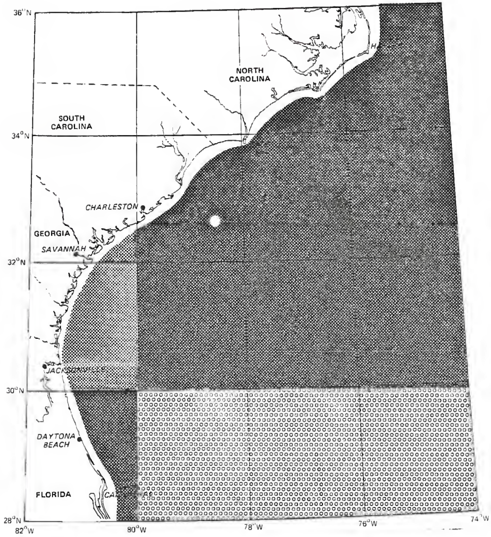


Figure 4-4C STD/CTD Station Data Density for Summer

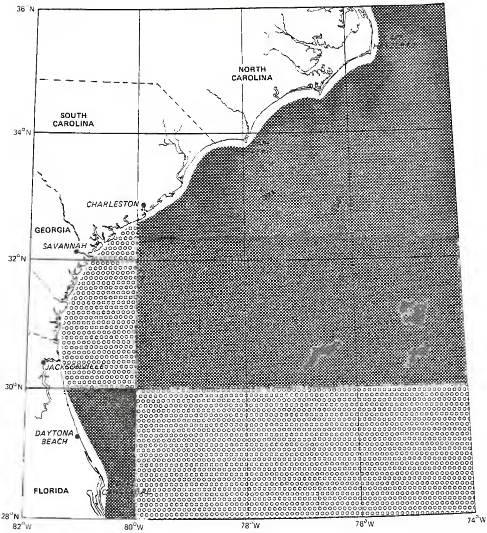


Figure 4-4D STD/CTD Station Data Density for Fall

sional) and time and is not readily assessed with the existing disjointed data sets and the large variance in the numbers and kinds of observations over the region. The nonuniform distribution of data in time over the years contributes in each case to certain levels of bias in each statistic or derived estimate. Quantitative estimates of error levels will be determined by the objective analysis program used to prepare the data for a particular model run.

In general, for diagnostic modeling as recommended here, density profiles need to be generated as input on a horizontal spatial scale compatible with the baroclinic radius of deformation for the region. For present purposes, this scale is on the order of 10 kilometers. Figure 4-5 shows an example for the nothern SAB region of a model grid constructed on the appropriate scale. For this subregion alone, 419 density profiles are necessary as initial input (Vertical resolution in each profile is a function of the number of levels in a particular model). The spatial non-uniformity of the existing hydrographic data base requires an interpolation scheme capable of providing best estimates of input data on a uniform grid of deformation radius scale. The temporal nonuniformity of the existing hydrographic data base at present dictates the upper limit of the resolved frequency as seasonal. Although some resolutation of higher frequency processes may be possible for specific subregions using a composite data base input, it seems likely that boundary value model input at higher frequencies will be possible only with suitably constructed remote sensing products in the future.

In order to obtain best estimates of density at uniformly spaced model grid points, it is necessary to utilize an appropriate objective analysis scheme that can be operationally applied to the existing nonuniform (in space and time) data base to consistently provide estimates of means and error levels. Levitus and Oort (1977) and Goodin, et al, (1979) have recently investigated such methods applied to oceanographic and meteorological data, respectively. A common approach to interpolation of sparse data onto a regular grid is to assume that the grid value is some weighted average of the surrounding data values. In an early study, Cressman (1959) reported on a procedure for use in pressure-surface height analysis which used a weighting factor dependent on R, where R is the distance at which the weighting factor goes to zero, i.e., the "radius of influence". This weighting technique aided the interpolation procedure in areas of sparse data. Decreasing values of R were used on successive scans to analyze a spectrum of

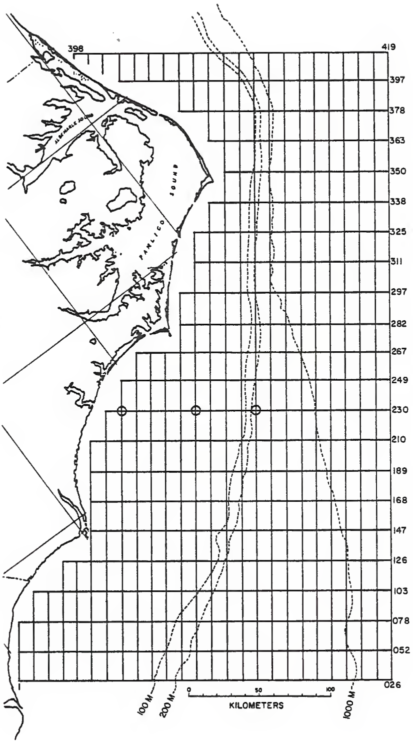


Figure 4-5 Typical approximately scaled model grid for a northern subregion of the SAOS

scales. The values obtained from each scan were then averaged to produce the final field. Endlich and Mancuso (1968) combined both polynomial fitting and distance weighting in their interpolation technique. A least-square fit to a first-order polynomial was performed using five of the nearest station values. Shepard (1968) discussed an interpolation technique in which a direction factor was also included which accounted for shadowing of the influence of one data point by a nearer one in the same direction. The method also included the effect of barriers. Shenfeld and Boyer (1974) presented a technique for interpolation of a velocity field similar to that proposed by Endlich and Mancuso. The computed wind velocity at any grid point was more dependent on nearby stations and was more dependent on downwind distance than on crosswind distance. For interpolation in regions of sparse data, Fritsch (1971) used a cubic spline technique. He first fitted spherical surfaces to the data for an initial field, and then iteratively adjusted these values using the splines until convergence was obtained. He compared his technique with that of Cressman using a data set with a known solution, and the mean error (3%) was approximately half that of Cressman's. MacCracken and Sauter (1975) used a Gaussian weighting scheme to eliminate complete dominance of a measuring station near a grid point. Hovland, et al, (1977), used an iterative scan procedure in which the radius of influence was decreased and the number of stations increased empirically on successive iterations. The advantage is that small-scale motions detected in an area of dense station coverage are not transmitted to outlying areas. Moreover, during the initial iterations, this procedure places significant weight on outlying stations which may be less reliable than those in the center of the region. Boone and Samuelson (1977) described the application of a distance and directional weighting technique to the display of air pollution data.

A second class of methods for producing a continuous surface over a grid is least-squares fit of a polynomial to the data points. The technique requires minimization of the goodness-of-fit to the data. Panofsky (1949) used third-degree polynomials to fit wind and pressure fields for weather map construction. The technique was modified for areas with sparse data by Gilchrist and Cressman (1954). The polynomial-fitting procedures were typically applied to the whole grid. Alternatively, the polynomial interpolation may be performed over areas within the influence of individual stations. Thiessen (1911) defined polygons over particular areas by assuming that each station is associated with the local region nearer to that station than to any other. A simpler technique is to triangulate the region using the station locations for the vertex positions. Lawson (1977) described a number of algorithms which perform this task. Once the triangle vertices have been established, a variety of interpolation schemes can be used. A natural extension of this idea is to use higher order polynomials to achieve slope continuity between adjacent triangles. Akima (1975) developed a method of bivariate interpolation and smooth surface fitting for irregularly spaced data based on a fifth-degree polynomial. McLain (1974, 1976) used a different polynomial fitting approach in which the domain is divided into triangular subregions by connecting the data points. A second-degree polynomial is fitted to each triangle using all data points with each value weighted according to the inverse square of its distance from the given triangle.

A third general technique, first presented by Gandin (1963), known as optimum interpolation, has proved useful for interpolation of synoptic-scale meteorological data (wind and temperature) for initializing global or synoptic circulation model (Dartt, 1972; Schlatter, 1975; Julian and Thiebaux, 1975; Thiebaux, 1975). The technique produces an interpolated field from data points irregularly spaced in both space and time. The interpolation function can be formulated directly in terms of statistical properties of the wind (temperature) field, i.e., past behavior determines the function's form. This implies, however, that a historical record of data values must be available in order to calculate these statistical properties (covariances). Moreover, the variance from the long-term mean of a wind measurement taken at a particular hour may not be useful for a mesoscale flow.

Since the interpolation of a set of sparse data does not have a unique solution, it is important that the calculation be done carefully, producing physically realistic surfaces. The interpolated field is critical to calculations such as divergence, contouring of data value, and initialization of transport calculations. In a comparison of a number of procedures for interpolating sparse data, Goodin, et al (1979), concluded that the second-degree polynomial fitting procedure with an R^{-2} distance-weighting scheme provides a good compromise between computational costs and the accuracy of the final surface adjacent to, and further away from, measurement stations.

One effect of averaging historical data with a weighted objective analysis technique is to give a smoothed representation of the temperature, salinity and density fields. In particular, features such as the Gulf Stream front are smoothed out and the gradient is decreased considerably compared to an instantaneous picture. The degree of smoothing is important in evaluating how well the solution compares with knowledge of the circulation in the real ocean.

It is possible to investigate to some extent, the sensitivity of the results to the particular form of the density data. Holland and Hirschman (1972) have demonstrated the effect of smoothing on the density field. The results show that the velocity field is somewhat smoother than before, but the transport pattern is only moderately changed. The maximum Gulf Stream transport decreased from 82 to 63 million m^3 sec^{-1}, but the latter value is still much larger than that dictated by the wind curl or that found in the homogeneous case. This suggests that the exact form of the density field may not be important in determining the large-scale features of the circulation pattern (at the equator, however, some anomalous gyres are much weaker for the smoothed density case suggesting that unreliable density data may be a problem).

Quantitative verification of a model is particularly difficult for currents since meaningful comparison of observed and computed vector quantities must involve both direction and magnitude. The interdependence of two vectors may be studied with the covariance tensor similar to the covariance of two scalars. The problem with statistical evaluations is that model performance is judged independently of physical processes and time scales. Since it is essential to determine the predictability of processes at different time scales, recourse can be had to spectral routines. This technique is limited, however, when physical episodes are of relatively short duration, and also it must be assumed that model parameters vary within the time span of an episode. These considerations led Simons (1974) to a verification analysis based on application of digital filters.

In general, the hydrographic data input into a particular model are adequate if the model output velocity field is identical within experimental error to the observed velocity field. To test this adequacy, Model Current Measurements (MCM) can be compared to Field Primary Current Measurements (PCM). The fundamental question is: within what statistical limits can the MCM and PCM data sets be considered identical? Assuming reliable calibration (both static and dynamic), these limits will then be related to individual sampling differences together with the variability of the medium over unresolved scales.

Estimates of the linear association between comparable MCM and PCM data sets are given by the sample correlation coefficients (sample covariance divided by the product of the sample standard deviations). Application of the normal test for significance of this statistic may indicate that the correlation coefficients were significantly different from zero in absolute value at the 1 percent level. Thus, a linear relationship existed between pairs of sample values. If the samples were identical, the slope of the resulting regression line would be unity. This slope can be determined in a consideration of the variance-covariance relations and the orientations of the principal axes. In addition, information contained in the time series can be investigated by an examination of the correlation functions.

The individual MCM and PCM autocorrelation functions detect the character of the dominant periodicities in each signal as well as give some indication of the nature of the random noise components. To check for correlation between MCM and PCM records for specific time and displacements (i.e., to check phase differences), the cross-correlation functions may be computed.

To quantify the comparisons further, the orientations of the covariance principal axes may be estimated, based on the sample variances and covariances, including the anisotropy which ranges between zero and unity; the closer it is to unity, the more significant is the interpretation of principal axis orientation. The principal axis is the orientation for which the covariance between samples vanishes. An orientation of 45° is indicative of samples that are identical in their lowest order statistics. Other statistical tests can be performed in addressing the question: how identical are the MCM and PCM samples? In the first test each T, U, V sample can be treated as a three-dimensional vector random variable whose probability density function is multivariate normal. Then, based on the sample statistics of these vectors, the hypothesis that the distribution means are equal can be tested at the .95 level or the .99 level.

A second test can be based on the inherent symmetry of the autocorrelation function. A criterion may be stated: if two signals are identical their cross-correlation function is symmetic. Thus, the mean value of the difference between cross-correlation values at ± each lag time is a measure of the asymmetry of the cross-correlation function or of the dissimilarity between signals. Interpretation of the magnitude of this parameter requires standardized tests and experience with known signals and fields. In general, the assessment of data adequacy for a particular model must be approached in a detailed, iterative, interactive way, and is a continual process occurring simultaneous with model development and implementation.

4.2 METEOROLOGICAL DATA

4.2.1 Meteorological Data Sources and Ships of Opportunity Data Analysis

There are three major sources of meteorological data for the South Atlantic Bight coastal regions: National Weather Service (NWS), National Climatic Center (NCC), and National Data Buoy Office (NDBO). The type and quality of these data sets are discussed in the following sections. All of these data are available through NCC in Asheville, NC. Specific information is given for the North Carolina coastal area as an example. NCC provides a detailed station list for the other areas. Locations for all observation sites mentioned below are found in Figures 4-6 and 4-7.

The first source, NWS, maintains observation stations at Savannah, GA., Charleston, SC, Wilmington, NC, Cape Hatteras (Buxton), NC and Norfolk, VA. Flight Service Stations (FSS) at New Bern, NC and Jacksonville, NC and the Cherry Point Marine Air Station provide hourly weather observations on a part-time basis for NWS. The FSS at Elizabeth City, NC provides similar observations, but is open only during daylight hours (8:00 a.m. to 6:00 p.m.).

NCC also catalogues data from various sources. There are five Coast Guard Stations and another Marine Air Station which take observations on a part-time basis. Also, lightships are maintained offshore at Frying Pan Shoals (Cape Fear) and Diamond Shoals (Cape Hatteras) from which three hourly observations are made.

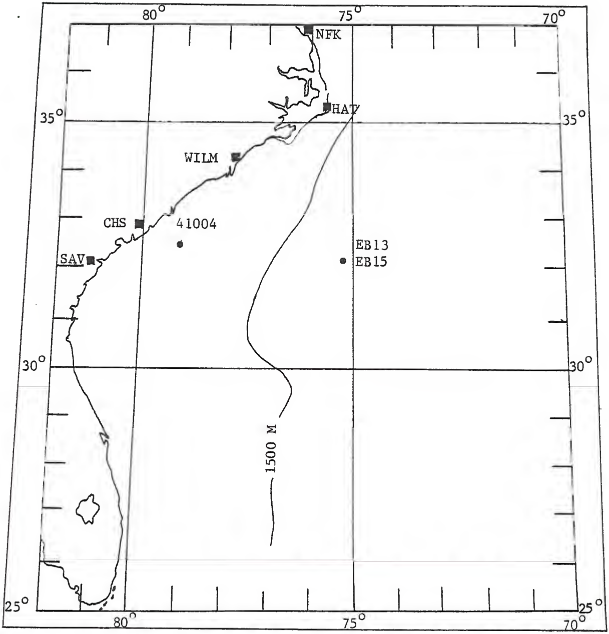


Figure 4-6 Location of National Weather Service observation stations (black squares) and meteorological monitoring buoys (black circles) located in the South Atlantic Bight.

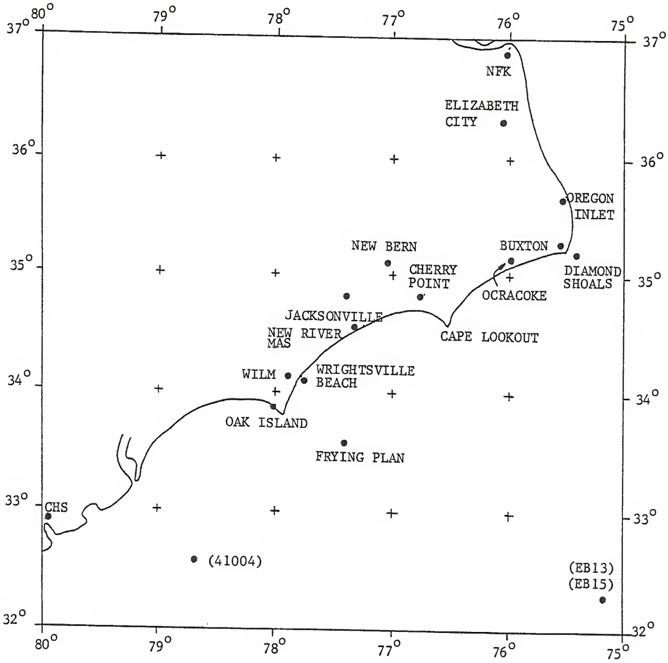


Figure 4-7. Location of meteorological monitoring stations along the North Carolina Coast (see Text, Section 4.2.1 for a more complete description).

NDBO provides the third data source. It maintains a series of meteorological data buoys at various locations off the United States. One buoy was in place about 300 kilometers east of Charleston for a little over two years (1973-1976). Another buoy was implaced about 40 kilometers east of Charleston during the summer of 1978.

The following sections are devoted to a discussion of the types of data provided by each of these sources. Also preliminary analysis has been performed on some of these data, the results of which are presented.

The NWS land-based reporting stations provide both a historical data base and current (hourly) observations. From the record of past observations, statistics can be developed to provide long term information at each of these stations by the day, month or season. These statistics will be quite accurate due to the long span of these records. However, if conditions offshore are required, it is not clear how the onshore stations can be extrapolated to meet this need.

This problem may be overcome by two methods. The first involves extrapolating the surface pressure field from land over the ocean. Experienced forecasters can do this with some confidence. Once this pressure field is constructed, surface winds can be estimated, but they may be subject to considerable error due to the random nature of the coastal boundary layer. A second method involves the use of time series analysis to compare meteorological data obtained offshore from a buoy or lightship with the corresponding observations from a coastal station. The results of this analysis show the frequency ranges for which the land observations approximate the marine conditions. A transfer function is obtained which constructs an offshore time series from the corresponding coastal series; an example of this technique is developed in Section 4.2.2.

Coastal and nearshore data are available from various locations. NWS stations at Norfolk, Cape Hatteras, and Wilmington save three hourly observations which are published monthly. Some statistical analysis is presented in these publications. The five Coast Guard stations and the Marine Air Station also save three hourly observations. These stations may not be occupied throughout the year, so there may be data gaps. These stations provide better longshore resolution than the NWS stations. Two lightships are maintained at Diamond Shoals (Cape Hatteras) and Frying Pan Shoals (Cape Fear). These are located a few tens of kilometers offshore and provide observations over the water. Three hourly data are collected at NCC from these stations. Mean conditions, time scales of variations, or comparisons with coastal stations are obtainable from this data set.

Meteorological observations taken by ships passing near the coast are available from NCC. These observations extend from the late 1800's to the present, and provide a widely distributed data source. However, analysis must be performed carefully as these data are biased in several ways.

Ships of opportunity data for the years 1973-1976, for the North Carolina coastal areas, were used to indicate potential problems with developing statistics. This data set was available and is used for a quick analysis. Saunders (1977) gives wind stress measurements from a 32 year record, but it is from the North Atlantic. His statistics are also for larger areas (1° squares). Nevertheless, useful information is obtained from this three year data set. Figures 4-8 through 4-19 show the data count for each month of the available records for .2° x .2° squares. The absence of a number indicates that no data are available for the square. There are only a few squares showing more than ten observations in any month. The area north of Cape Hatteras has a more uniform distribution of samples than that south of Hatteras. Some squares show many observations which correspond to shoal or channel markers used by ships as navigation check points.

As a test statistic from this data set, the mean surface temperature was calculated for each month. It is expected that the surface temperature field will be much steadier than the wind field. However, the presence of the Gulf Stream off North Carolina provides large temperature fluctuations which are due to the location of the Gulf Stream and the presence of spinoff features from the main stream. The surface temperature means show a reasonable structure, but the values are quite variable. One bias is apparent from these temperature values. Even though the variance of the means is low, there is no way to tell if the sample is uniformly spaced over the three years. A better statistical approach is to obtain averages for each month of each year within the squares and then average these separate monthly means. Inspection of the monthly means will indicate how the samples are spaced over the various years under consideration. A ten year data

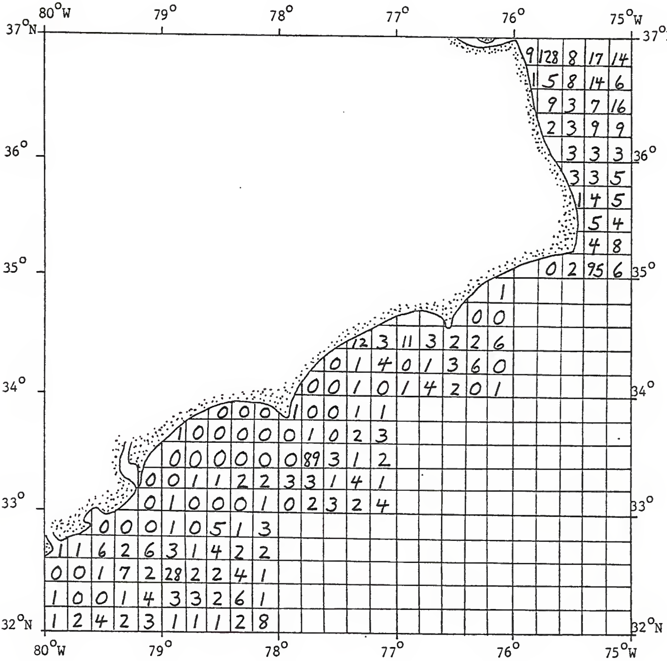


Figure 4-8 Wind Stress Observation Count for January, .2° x .2° squares.

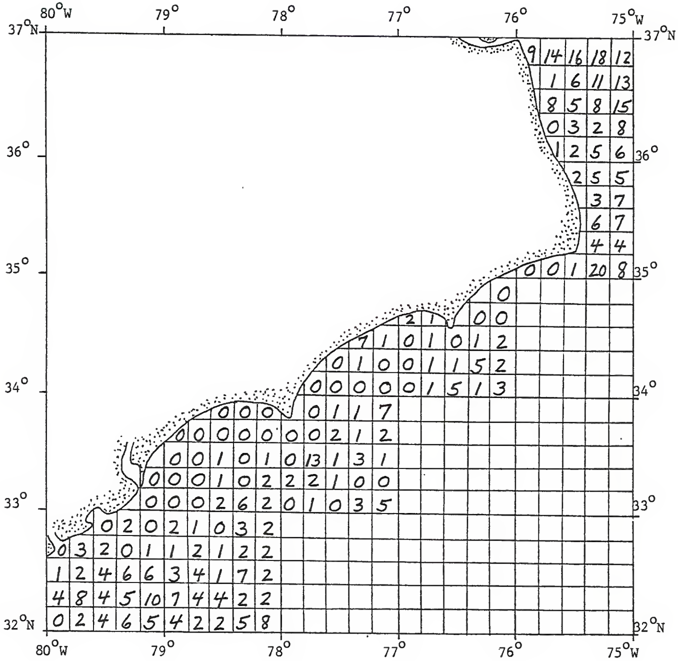


Figure 4-9 Wind Stress Observation Count for February, .2° x.2° squares.

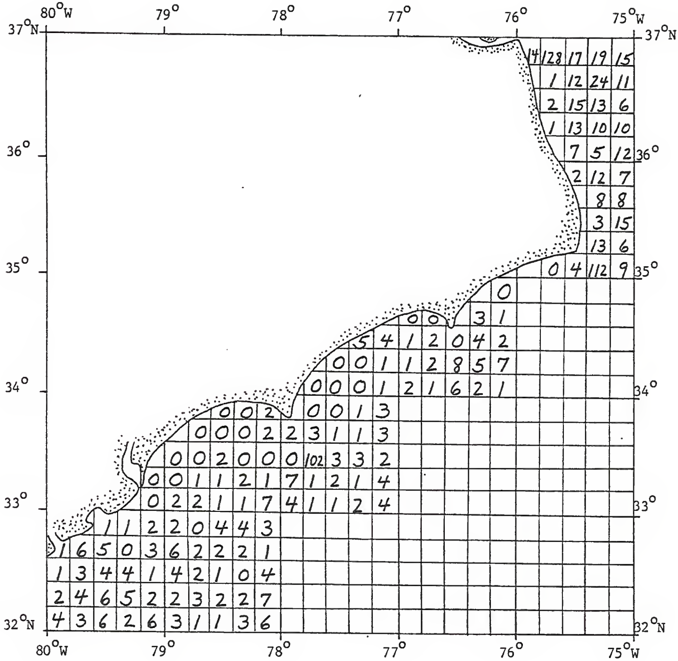


Figure 4-10 Wind Stress Observation Count for March, .2° x .2° squares.

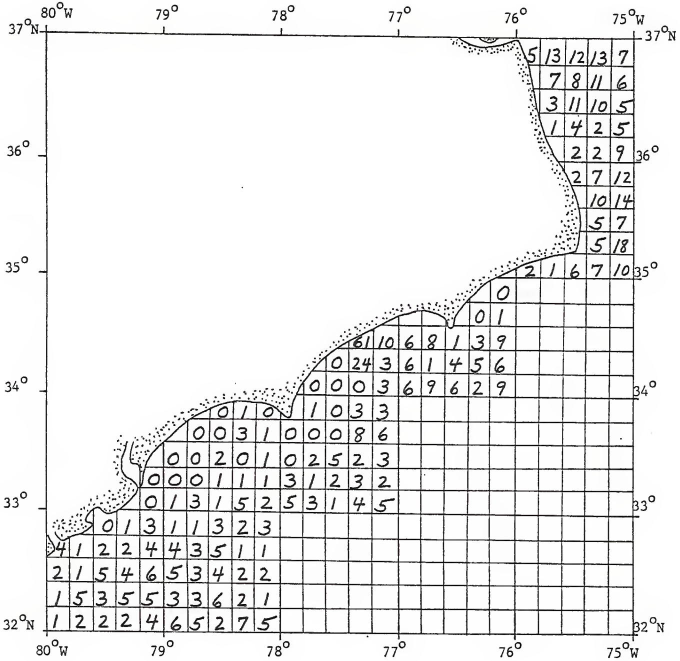


Figure 4-11 Wind Stress Observation Count for April, .2° x.2° squares.

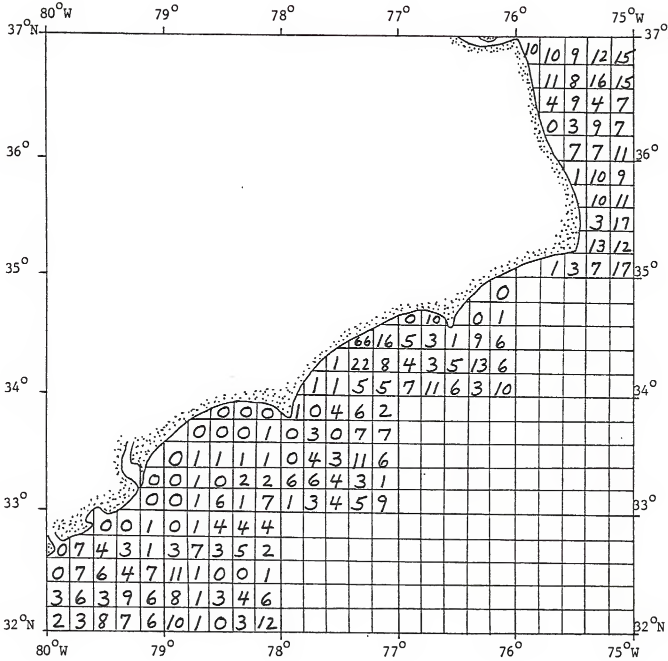


Figure 4-12 Wind Stress Observation Count for May, .2° x.2° squares.

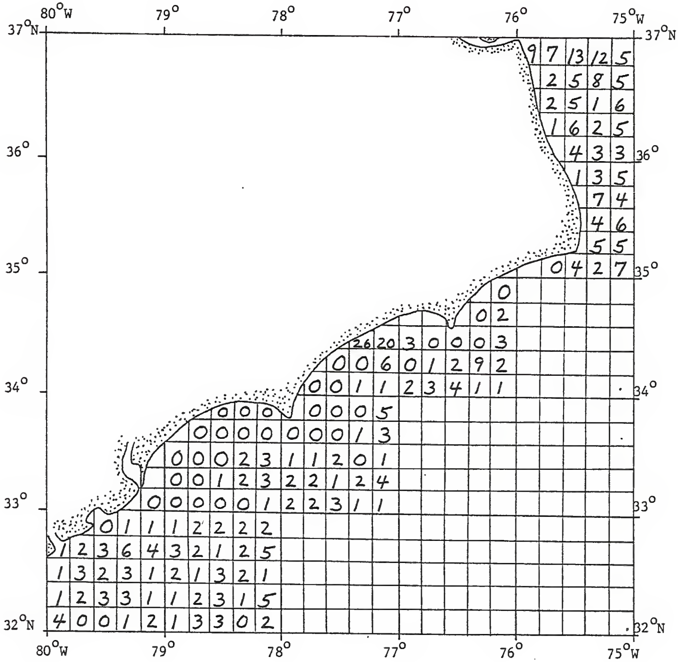


Figure 4-13 Wind Stress Observation Count for June, .2° x.2° squares.

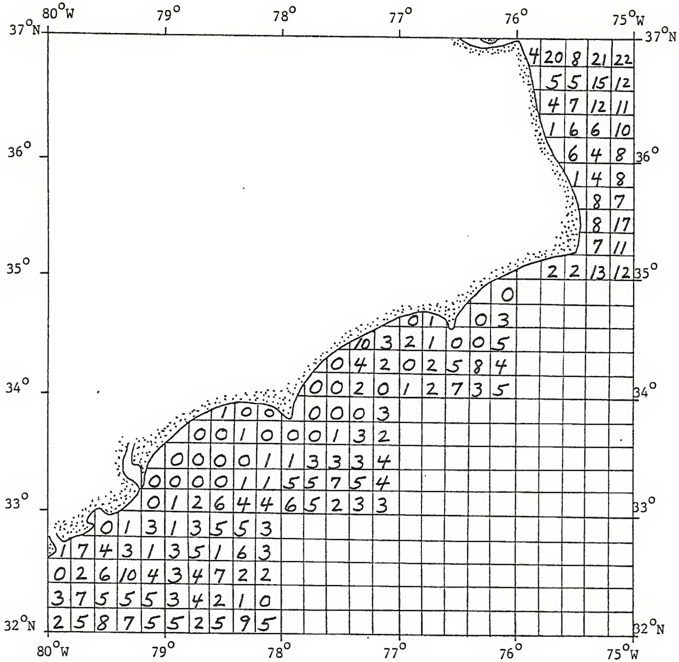


Figure 4-14 Wind Stress Observation Count for July, .2° x .2° squares.

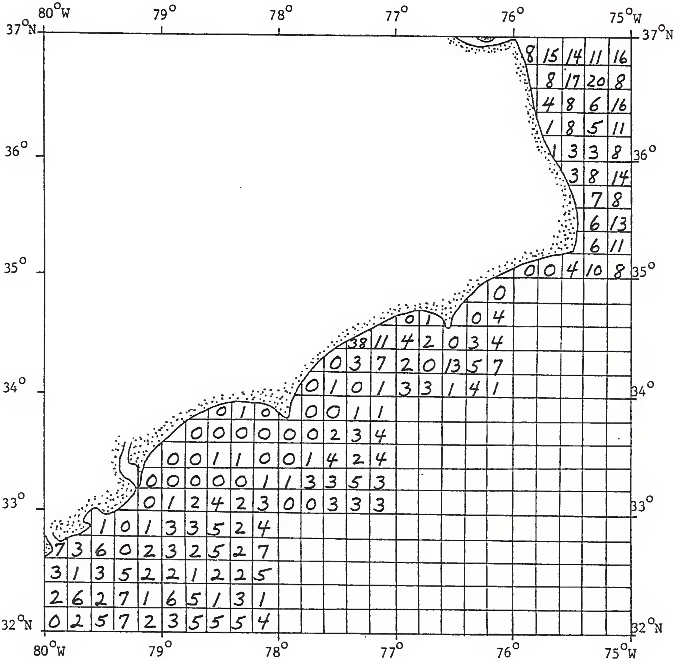


Figure 4-15 Wind Stress Observation Count for August, .2° x .2° squares.

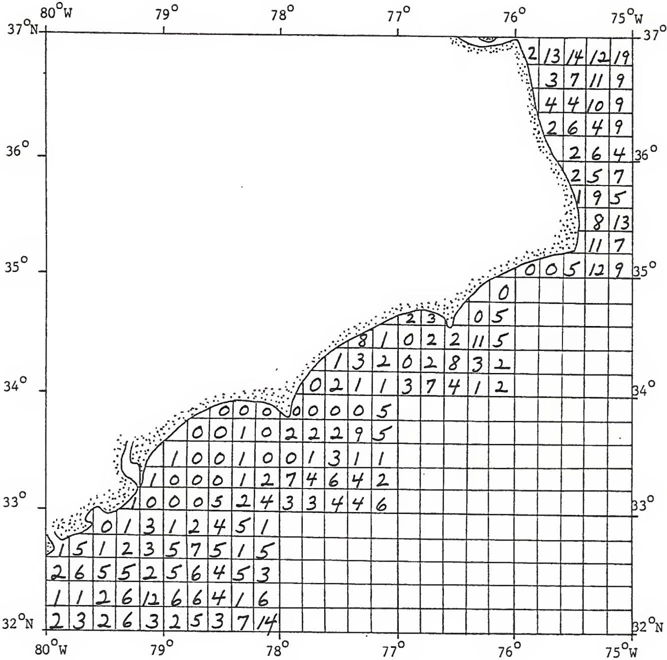


Figure 4-16 Wind Stress Observation Count for September, .2° x .2° squares.

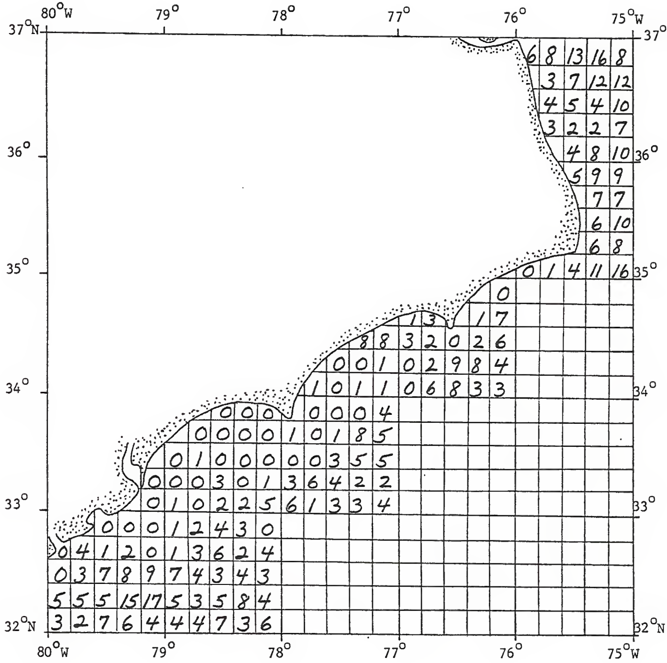


Figure 4-17 Wind Stress Observation Count for October, .2° x .2° squares.

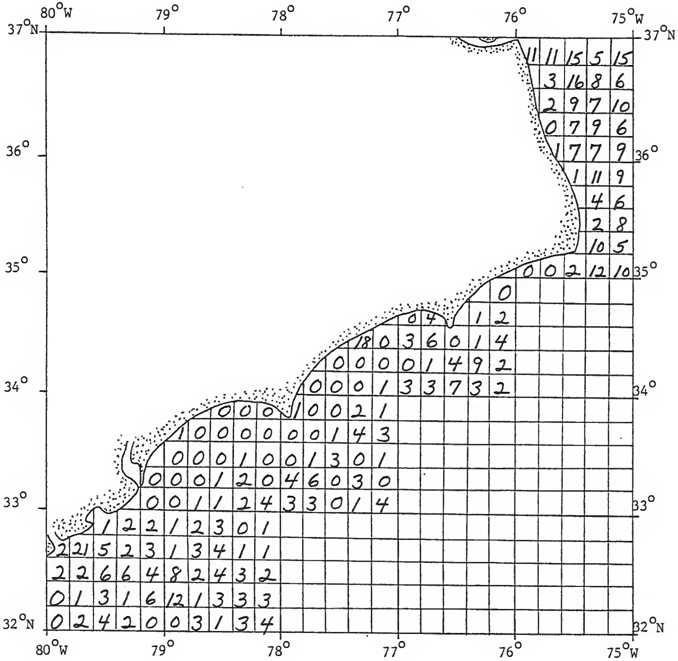


Figure 4-18 Wind Stress Observation Count for November, .2° x 2° squares.

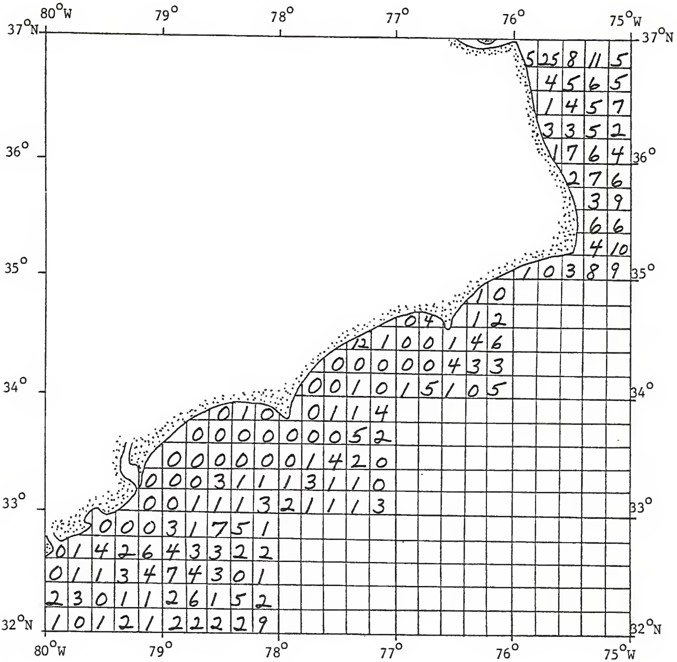


Figure 4-19 Wind Stress Observation Count for December, .2° x .2° squares.

set should be adequate for temperature statistics.

The surface wind is more important for determining oceanographic conditions than the surface temperature field. The wind is highly variable and it is expected that much larger numbers of observations are necessary to get stable statistics. This was tested by computing average monthly wind velocity for the three year record. A similar study by Weber (1978) considered monthly averages in 1° squares from ten years of ship observations (Figures 4-20 through 4-31). Comparison of these two studies will indicate the reliability of the three year statistics. The response from the ten year study indicates a consistent wind pattern over the entire North Carolina coastal area for the month of September. Figure 4-32 is the result for this month from the three year record. It shows considerable scatter. This variability is due to averaging over smaller spatial areas and shorter time spans. This preliminary work indicates that all of the available observations must be included to obtain good means if adequate horizontal resolution is desired. It seems to be unreasonable to expect good statistics from .2° squares with less than 100 years of observations. Fifty years of data should give reasonable results in .5° squares.

NDBO implaces meteorological buoys at various locations off the United States. These bouys are not yet maintained as permanent data sources, but it may happen that a buoy is in a convenient place at a convenient time. Two buoys (EB13 and EB15) were implaced consecutively at the same location 300 kilometers east of Charleston, S. C. covering the period December 1978 through October 1976. A third buoy (41004) was implaced in June 1978 about 40 kilometres east of Charleston and is still operational. The data collected by the buoys are telemetered to shore periodically, so up-to-date information is available. Comparison of the buoy data with coastal stations will give insight into the variability of weather conditions on either side of the land-sea boundary. This is the subject of Section 4.2.2.

In summary, the land based weather stations provide an adequate historical data base for obtaining reliable meteorological statistics. Offshore data from lightships can provide meaningful statistics to be compared with those from land stations. The ships of opportunity data present a special problem and can be used only for climatology and not for real-time observations. For good spatial resolution, very large numbers of records are required. Saunders (1977) shows

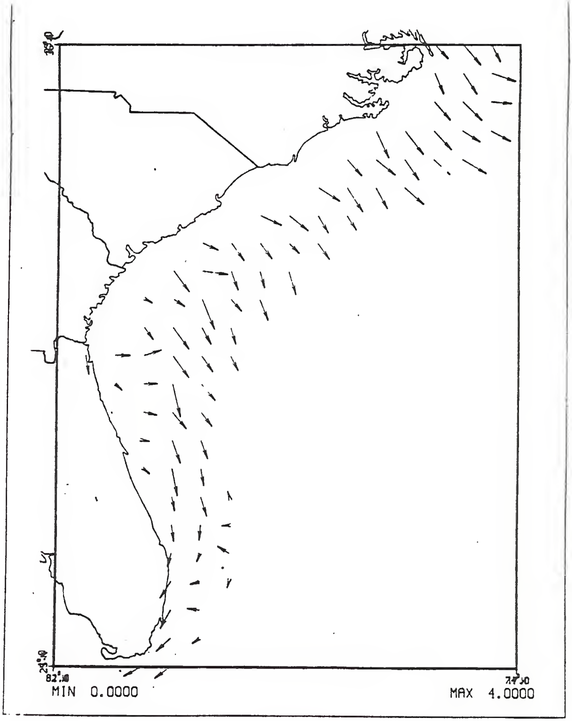


Figure 4-20 January mean wind (Weber, 1978), 1° x 1° squares

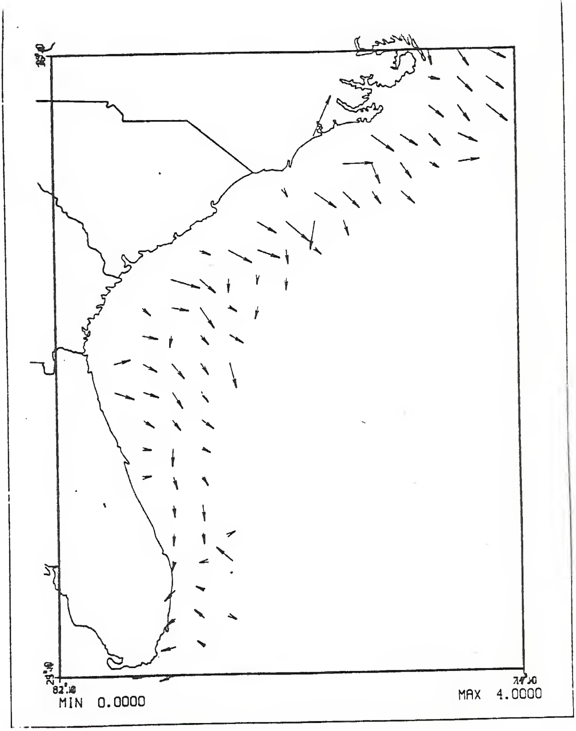


Figure 4-21 February mean wind (Weber, 1978), 1° x 1° squares

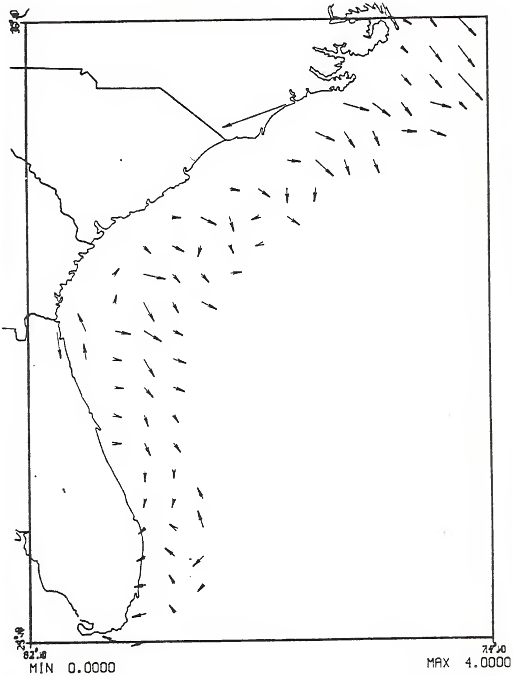


Figure 4-22 March mean wind (Weber, 1978), 1^{o} x 1^{o} squares

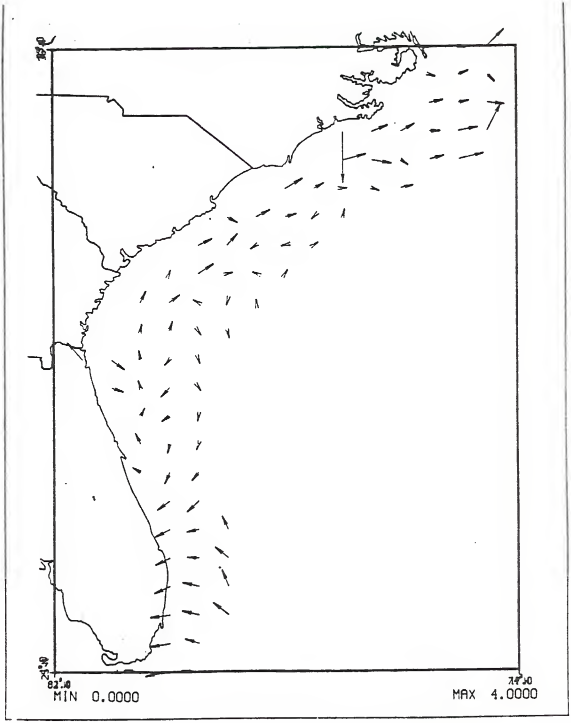


Figure 4-23 April mean wind (Weber, 1978), $1^{\circ} \times 1^{\circ}$ squares

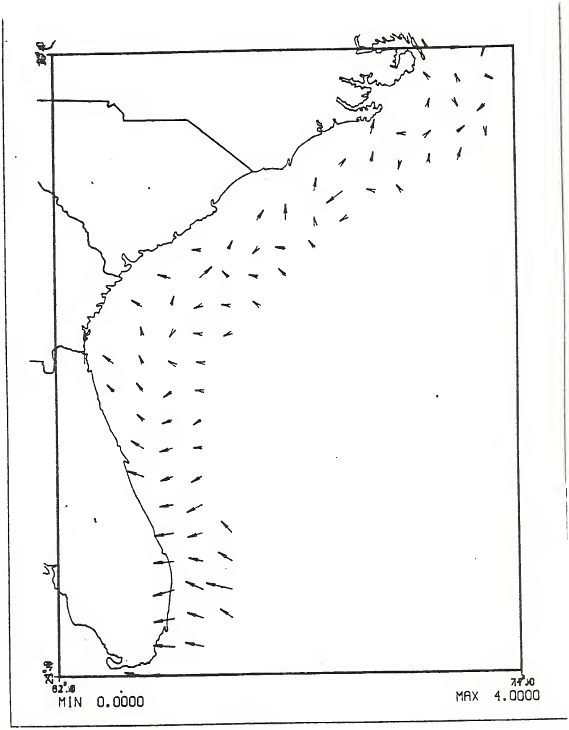


Figure 4-24 May mean wind (Weber, 1978), 1° x 1° squares

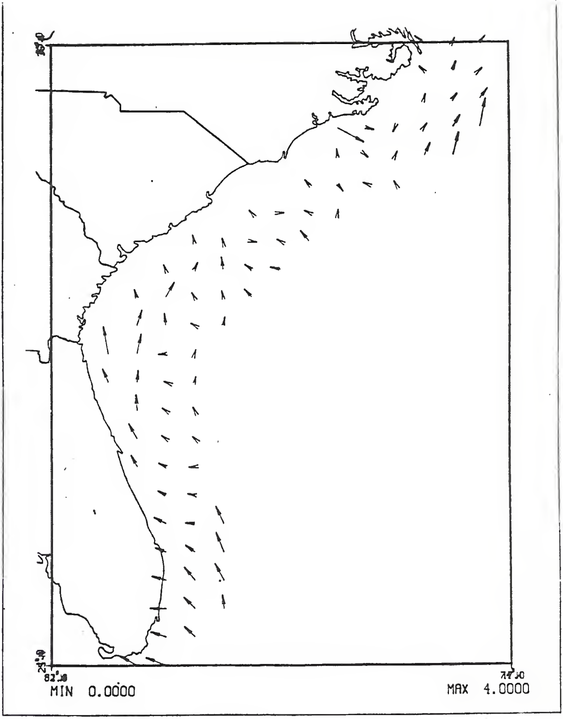


Figure 4-25 June mean wind (Weber, 1978), 1° x 1° squares

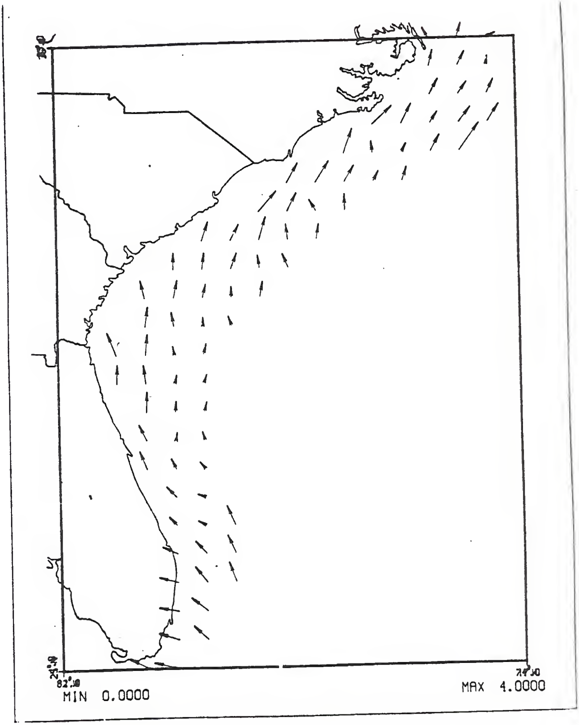


Figure 4-26 July mean wind (Weber, 1978), $1^{\circ} \times 1^{\circ}$ squares

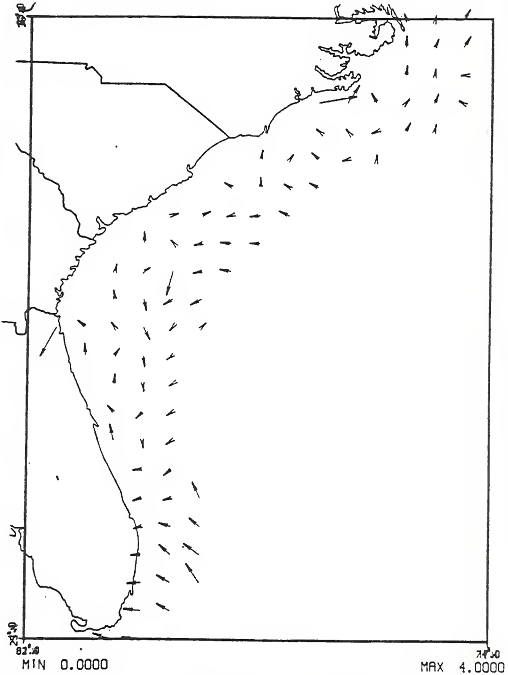


Figure 4-27 August mean wind (Weber, 1978), 1° x 1° squares

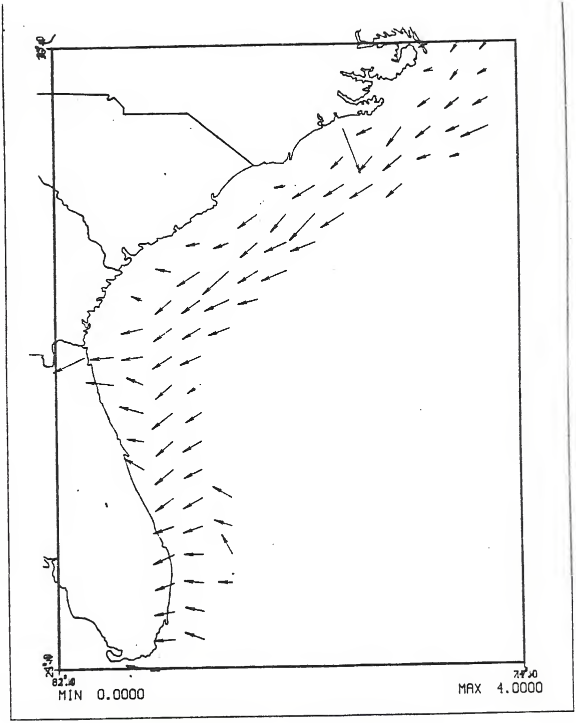


Figure 4-28 September mean wind (Weber, 1978), $1^{o} \times 1^{o}$ squares

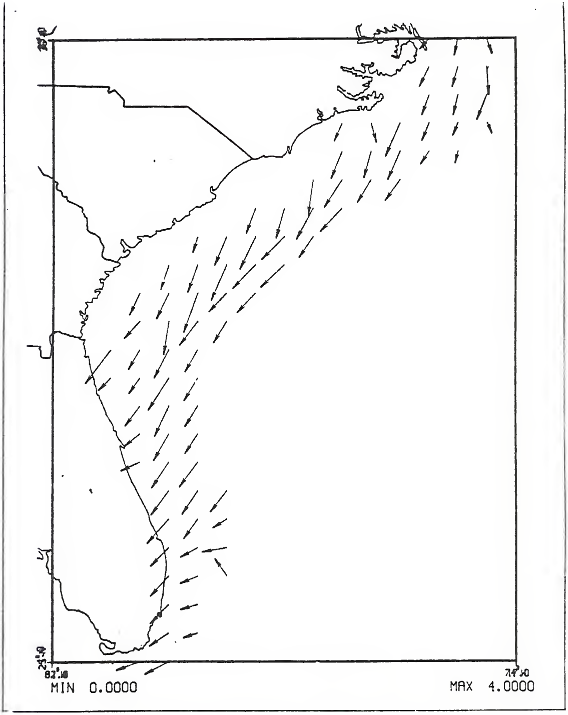


Figure 4-29 October mean wind (Weber, 1978), 1° x 1° squares

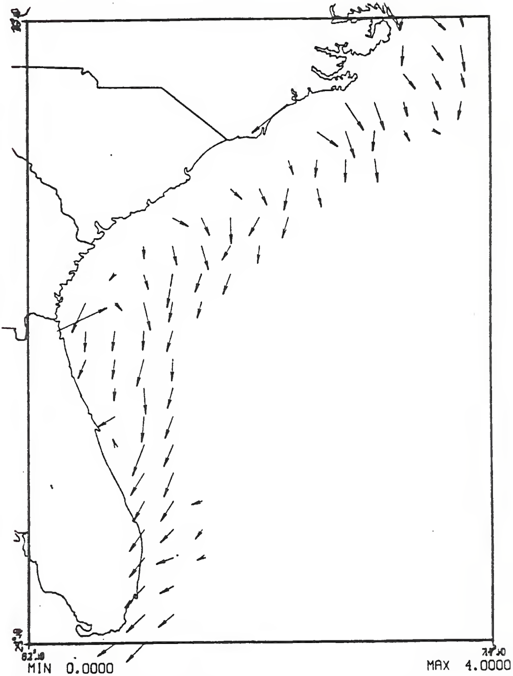


Figure 4-30 November mean wind (Weber, 1978), $1^{\circ} \times 1^{\circ}$ squares

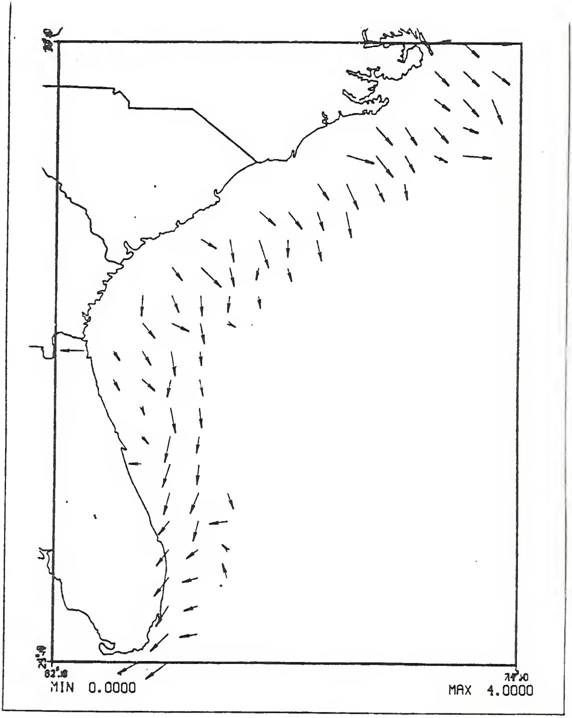


Figure 4-31 December mean wind (Weber, 1978), $1^\circ \times 1^\circ$ squares

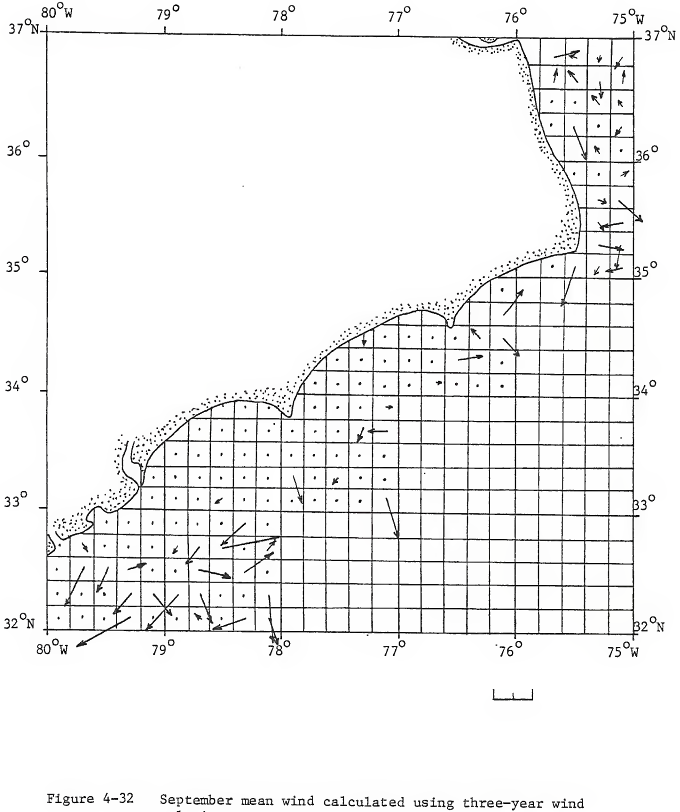


Figure 4-32 September mean wind calculated using three-year wind velocity records from all sources. Dots indicate squares for which data counts are zero.

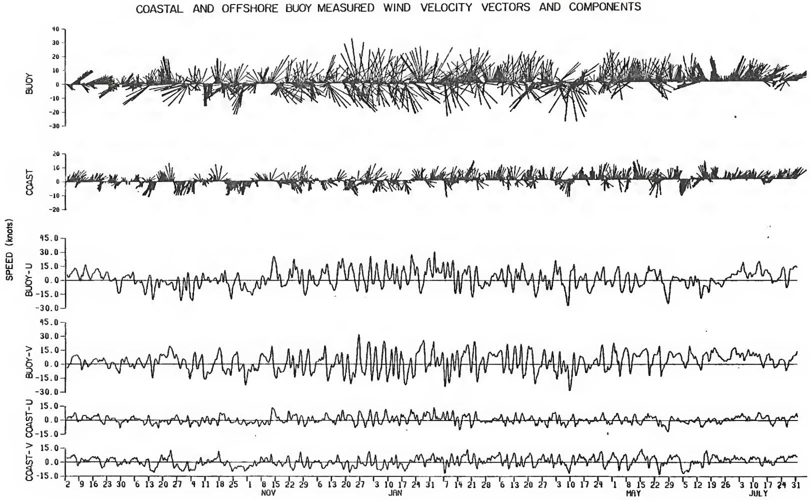
that even with 32 years of data and 1° squares, the means must be averaged over three months to obtain reasonable error reduction. The present study shows that three years is a woefully short record for adequate climatology. Although there are over-the-water measurements of near surface meteorological parameters being collected at the Savannah, Frying Pan Shoals, and Cape Lookout lights. The meteorological monitoring buoys located in the South Atlantic OCS area of immediate interest show the greatest potential for providing the long term statistical information of greatest value to BLM in calculating wind field data. These buoys also will provide the time series necessary for comparison with shore station data which can be used in the transfer function analysis (see Section 4.2.2 of this report) to greatly increase the amount of useful wind data. At the present time, the data from the buoys may not be available when it is desired because of lag time in processing; however, these buoys are the most important source of near real-time offshore observations.

4.2.2 Relationship Between Winds Observed at the Coast and Offshore

4.2.2.1 Comparison of Observed Winds

Surface trajectory, interior circulation, and some bottom transport models require surface winds as input. Coastal wind observations are generally available and historical data bases have routinely been used for hindcast simulations or for construction of probabilistic transition matrices for the case of surface trajectory models. Observations of offshore winds are generally not available in the detail required for these applications. Since offshore winds can differ markedly from coastal wind, the use of the latter in simulation models for the purpose of risk analysis can result in significant error.

This section presents a comparison of winds observed on the coast at Charleston, S.C. with winds observed some 300 kilometres offshore to the east on an NDBO meteorological data buoy over the one-year period spanning August 1975 to August 1976. The data are shown in Figure 4-33. Plotted as a function of time are three hourly northward - v and eastward - u wind velocity components and wind velocity vectors. From top to bottom they are the coastal and offshore vectors, coastal components, and offshore components. The striking comparison is the difference in magnitude between the two data sets. Although correlated, the mag-



COASTAL AND OFFSHORE BUOY MEASURED WIND VELOCITY VECTORS AND COMPONENTS

Figure 4-33 Observed Coastal and Buoy Sticks and Components
Wind velocity vectors and northward - v and estimated eastward - u velocity components observed at the Charleston,S.C. coast and offshore some 300 Km to the east. The sampling interval is 3 hours. Positive means that the wind is blowing toward the north or the east.

nitudes of the offshore wind fluctuations may be two to four times those at the coast. The winds are also seasonal. During the winter months, most of the variance is contained in synoptic scale events with periodicities of 2-5 days. Summer events are of longer duration and lesser magnitude.

4.2.2.2 Data Analysis

Two types of analysis will be presented. The first will develop the statistics of the coastal and offshore winds as averaged over the full one year sample. Emphasis will be given to the correlation between the velocity components and the ability to predict offshore winds given the coastal data. The analysis in this case will be site specific. Other techniques not discussed herein can be used to generate wind fields. The site specific results show the extent to which wind field generation by coastal observations is feasible. A set of transfer functions are derived in a linear least square error sense upon which the coastal winds can be operated in order to estimate the offshore winds. The second analysis procedure will elucidate the seasonal variabilty of the observed coastal and offshore winds. The seasonal modulation in the kinetic energy density, structure, and correlation will be developed.

Linear mean square estimation plays a central role in the analysis. Consider the northward offshore wind component v_B as being the linear combination of coastal wind components u_C and v_C plus a random error ε , where the subscripts B and C denote bouy and coast respectively. Written as an equation:

$$v_B = \int_{-\infty}^{\infty} h_{u_C\, v_B}(\tau)\; u_C(t - \tau)d\tau + \int_{-\infty}^{\infty} h_{v_C\, v_B}(\tau)\; v_C(t - \tau)d + \varepsilon_{v_B} = \hat{v}_B + \varepsilon_{v_B}$$

where $\hat{v}_B$ is the estimated northward wind component at the buoy based upon the coastal wind velocity and εv_B is the estimation error, τ is a time lag in hours, and the integration is performed over all positive and negative lags. Thus, the full memory of the combined coastal and offshore meteorological system is maintained and the offshore wind may either lag or lead the coastal winds. Similarly, let u_B be represented as the linear combination:

$$u_B = \int_{-\infty}^{\infty} h_{u_C u_B}(\tau)\ u_C(t - \tau)d\tau + \int_{-\infty}^{\infty} h_{v_C u_B}(\ )v_C(t - \tau) + \varepsilon_{u_B} = u_B + \varepsilon_{u_B}$$

Linear mean square estimation is the procedure which minimizes the errors ε_{v_B} and ε_{u_B} defined as

$$\varepsilon_{v_B} = (\nu_B - \nu_B)^2$$

and

$$\varepsilon_{u_B} = \overline{(u_B - \hat{u}_B)^2}$$

It is most easily performed in the frequency domain after taking Fourier transforms of the velocity components and the weighting functions or impulse response functions h(τ). The Fourier transforms of the h(τ) are defined as transfer functions H(f) where f denotes frequency. In terms of the auto and cross spectral estimates between the various wind components, the transfer functions computed in a manner that minimizes the errors ε above are given by:

$$H_{v_C u_B} = \frac{S_{v_C u_B}\ S_{u_C u_C} - S_{v_C u_C}\ S_{u_C u_B}}{A}$$

$$H_{u_C u_B} = \frac{S_{u_C u_B}\ S_{v_C v_C} - S_{u_C v_C}\ S_{v_C u_B}}{A}$$

$$H_{v_C v_B} = \frac{S_{v_C}\ S_{u_C u_C} - S_{v_C u_C}\ S_{u_C v_B}}{A}$$

$$H_{u_C v_B} = \frac{S_{u_C v_B}\ S_{v_C v_C} - S_{u_C v_C}\ S_{v_C v_B}}{A}$$

Where $A = S_{v_C v_C}\ S_{u_C u_C} - |S_{v_C u_C}|^2$ and the subscripted quantities S are the smoothed auto and cross spectral estimates between the various pairs of velocity components denoted by the subscripts. The derivations of the transfer functions are discussed in Bendat and Piersol (1972) and other texts on time series analysis. They are complex quantities having an amplitude and a phase. The amplitude is the multiplier applied in the frequency domain to transform, for example, v_C into v_B and the phase is the shift in radians (or equally in time) alignment by which v_C lags or leads v_B at a given frequency.

Smoothing or averaging is required to reduce random errors. For example, with no smoothing, the random errors would be 100% and even totally uncorrelated data could be reproduced identically. The transfer functions, however, would have no bearing on future estimation attempts, and therefore, would be statistically meaningless. For the purposes of computing the year long statistics, the data were Fourier transformed, spectral estimates were computed, and they were then averaged over a bandwidth of $B = 1.383 \times 10^{-3}$ c.p.h. Given a record length of 366 days this translates to approximately 24 degrees of freedom. Consequently, the random errors are reasonably small and the appropriate significance levels or confidence intervals are shown in the statistical representations to follow.

As estimators, transfer functions can only account for the portion of the data which is correlated. Thus, the variance of the estimated time series will be less than the variance of the time series to be estimated. Coherence functions are measures of the correlation between time series as a function of frequency. Specifically, the coherence squared is the portion of variance in one time series that may be accounted for and hence estimated, via linear relations with another, or a set of, time series at a given frequency. There are several different measures of coherence, five of which will be discussed herein. These include ordinary coherencies, maximum and minimum coherencies, partial coherencies, and multiple coherencies. Each will be explained at the appropriate time. The square of the coherence function or coherence squared will be used throughout since this gives the measure of variance that can be accounted for, e.g., a multiple coherence squared of 0.8 suggests that 80% of the variance in one time series can be accounted for by linear relationships with the others.

After considering the variance structure, the coherencies between coastal and offshore wind velocity components, and the transfer functions, the offshore winds are estimated from the coastal winds via complex multiplication in the frequency domain and inverse Fourier transformation. The observed and estimated offshore winds are then displayed for visual comparison.

The seasonal variability of the coastal and offshore wind velocity time series is explored by breaking the year long records into 2 month overlappping pieces. Statistics are then presented as a function of frequency and time in the form of contour plots using an averaged bandwidth of 4.56×10^{-3} c.p.h. which translates into approximately 13 degrees of freedom.

4.2.2.3 Year Long Statistics

The distribution of variance as a function of frequency is given by the spectral energy density function. Figure 4-34 shows the kinetic energy density spectra for the observed coastal and offshore wind velocity components. The ordinate gives the energy density in knots squared per cycle per hour (i.e., variance per unit frequency) as a function of frequency on the abscissa. The inverse of frequency in cycles per hour is the period in hours which is shown on the top of each figure. Offshore winds measured on the meteorological buoy are indicated by a solid line while coastal wind observed at Charleston are indicatd by a dashed line. At both locations, most of the variance occurs at time scales between 2-5 day periodicities. The v components also show peaks at about 9 days. These are the dominant periodicities of the weather variations; the shorter time scale being more prevalent during the winter months.

The coastal and offshore variance distributions are quite similar except for considerably large magnitudes offshore. This factor which is of paramount importance for circulation modeling and risk analysis is real and not just a matter of sample biasing by a moving platform. Note that the coastal and offshore spectra coalesce at high frequency. If buoy motions were significantly biasing the offshore record, then the expectation would be for large discrepancies at the high frequency end. Thus, the implications from the spectra are that the offshore and coastal variances have similar time scales, but that the synoptic weather offshore is much more energetic. The exception to this occurs at a periodicity of 24 hours corresponding to the sea breeze. Since the sea breeze is a local coastal phenomena, a peak exists at the coast, but not at the buoy.

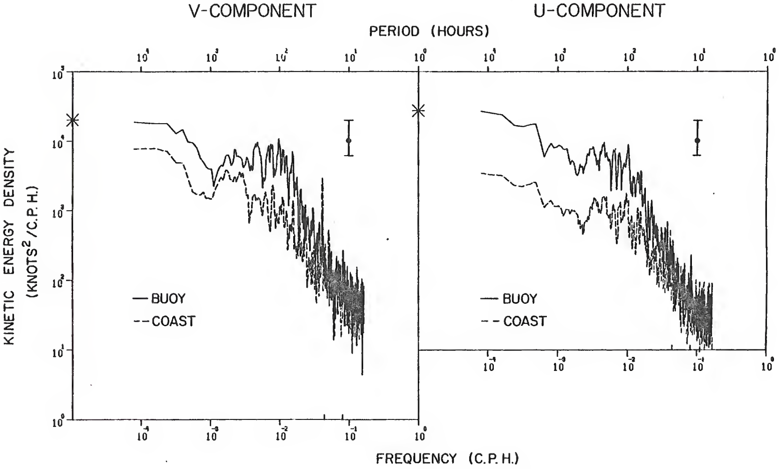


Figure 4-34 Component Spectra

Northward - v and eastward - u wind velocity component kinetic energy density spectra for the coast and offshore stations. The solid lines are the offshore spectra and the dashed lines are the coastal spectra. The 95% confidence interval for random errors with 24 degrees of freedom is given in the upper right.

The wind vectors rotate as a function of time. Figure 4-35 shows the rotary kinetic energy density spectra at the buoy and at the coast. The ordinates and abscissas are the same as for Figure 4-34. Negative, or clockwise, rotation is denoted by dashed lines. Both the offshore and coastal winds show a preference for clockwise polarized wind vectors. This behavior is compatible with the propagation of cyclonic systems offshore whose centers are to the north of the observation point. Thus, the wind vectors at both the coastal and offshore regions near Charleston, S.C. primarily rotate clockwise. The distribution of variance is very similar at the coast and offshore with the exception again of the sea breeze while the offshore magnitudes are much higher. For example, comparing the synoptic scale peak at about a 5 day periodicity, when averaged over the full year, the offshore clockwise variance is 3.6 times the coastal variance which states that the velocity fluctuations at 5 day periodicities offshore are 1.9 times as large as those at the coast when averaged over one year.

Table 4-2 shows the means and variances computed for each velocity component averaged over the full year.

Table 4.2 Means and Variances Averaged Over the Year
366 Days from August 1975 to August 1976

	v_C	u_C	v_B	u_B
Mean (kts)	0.9	0.7	2.8	1.9
variance (kts^2)	40.9	26.4	122.7	105.0
r.m.s. (kts)	6.4	6.1	11.1	10.3

The magnitude differences for the entire energy content of the offshore and coastal records are very similar to the synoptic scale portion. In terms of total variance, the r.m.s. offshore speeds are therefore 1.8 times the r.m.s. coastal speeds averaged over all frequencies for one year.

Since the velocity components look fairly similar except for magnitude, their coherency should be high. Figure 4-36 shows the ordinary coherence squared between v components at the coast and buoy and between u components at the coast

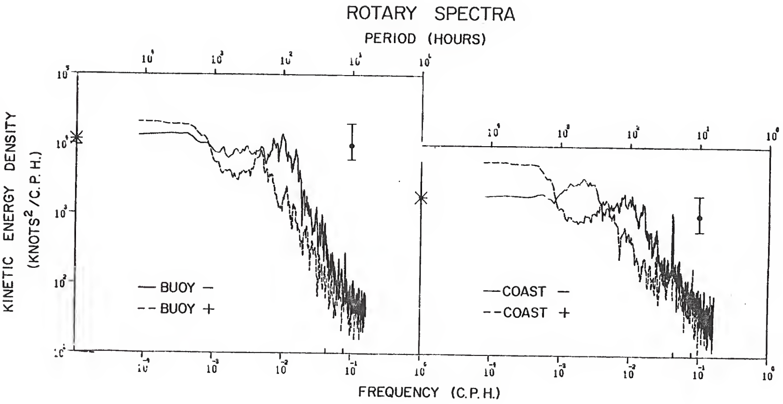


Figure 4-35 Rotary Spectra

Rotary kinetic energy density spectra for wind velocities measured on the coast and offshore. Solid lines denote clockwise polarization and dashed lines denote anticlockwise polarization. The 95% confidence interval for random errors with 24 degrees of freedom is given in the upper right.

WIND VELOCITY COMPONENT COHERENCE SQUARED AND PHASE

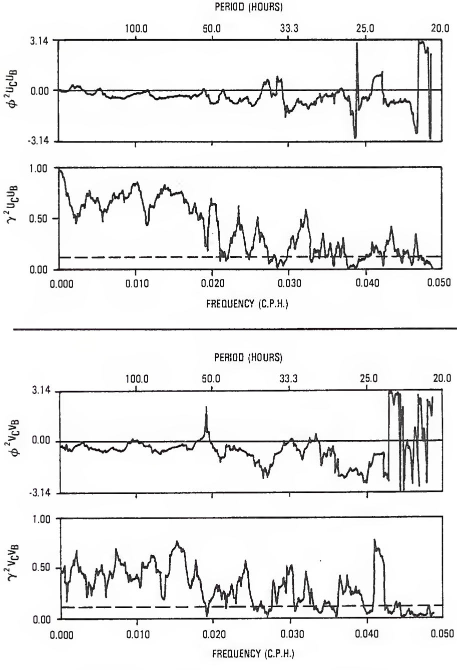


Figure 4-36 Ordinary Coherence Squared and Phase

The ordinary coherence squared and phase between similar wind velocity components observed at the coast and offshore. The 10% significance level for coherence squared with 24 degrees of freedom is indicated by a dashed line.

and buoy. The ordinary coherence squared measures the amount of variance in common between an input time series (in this case an offshore component) without regard to other correlated input. Thus ordinary coherencies may be biased upward or downward depending upon the presence of a second correlated input. The upper plate shows the coherence squared and phase between u components at the coast and at the buoy. The coherence is very high for periodicities longer than 2 days and the offshore oscillations lag the coastal ones implying offshore propagation of cyclonic disturbances as suggested by the rotary spectra. The lower plate offers a similar presentation for the v components. The results are nearly the same except for a somewhat reduced coherence at synoptic scales. The v components are very coherent at the 24 hour periodicity. Since the sea breeze doesn't extend so far offshore, this coherence probably reflects the diurnal tide.

The biasing of the ordinary coherence by other correlated inputs may be reduced by removing the influence of other inputs. The result is called a partial coherence function. A third coherency measure may also be calculated by including all known inputs in the calculation. This third quanitity is called a multiple coherence. Figure 4-37 shows the partial and multiple coherencies squared between the coastal v and u (the inputs) and the buoy u (the output), and between the coastal v and u (the inputs) and the buoy v (the output). The left hand plates correspond to u_B as output and the right hand plates correspond to v_B as output. The inputs for both are the same. The bottom plates give the partial coherencies squared between v_C and u_B or v_B after removing the influcence of u_B by linear mean square estimation. The middle plates give the partial coherencies squared between u_C and u_B or v_B after removing the influence of v_C by linear mean square estimation. The upper plates give the multiple coherencies squared between the two inputs v_C and u_C and the single outputs being either u_B or v_B. The 90% significance levels for the multiple coherencies are somewhat higher since degrees of freedom are lost upon increasing the number of inputs and the probability distribution functions for the partial, multiple, and ordinary coherencies are slightly different, for example, see Jenkins and Watts (1968) or other texts on time series analysis.

The multiple coherence squared is very high for the offshore u component. Roughly 80% of the offshore u variance can be accounted for by linear relationships with the coastal wind velocity vector at synoptic scales, i.e., per-

PARTIAL AND MULTIPLE COHERENCIES AVERAGED OVER A FULL YEAR

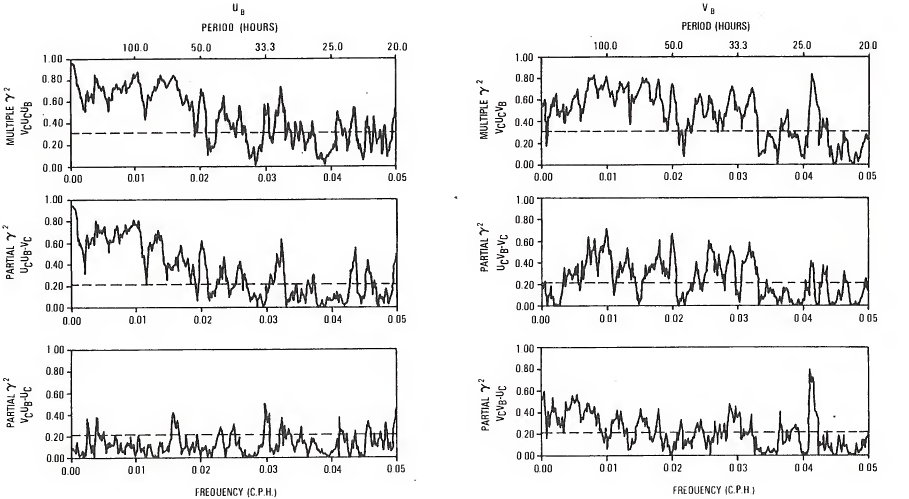


Figure 4-37 Partial and multiple coherency squared between the northward and eastward wind velocity components observed offshore, v_B and u_B, respectively, with their counterpart components observed at the coast v_C and u_C. The 10% significance levels are indicated by dashed lines for 24 degrees of freedom.

iodicities longer than about 2 days. The partial coherence squared $u_C\ u_B - v_C$ is very high for synoptic scales while that for $v_C u_B - v_C$ is very low at all frequencies. Consequently, the u_B oscillations are primarily related to the u_C oscillations and not to the v_C oscillations when averaged over the full year.

The multiple coherence squared for the v component at the buoy with the coastal velocity vector is also high. Roughly 70% of its variance at synoptic scales can be accounted for by linear relationships with the coastal winds. The partial coherencies, however, do not offer a picture which is as clear cut as that for the u component. For v_B, both u_C and v_C are important to varying extents. The exception is the 24 hour peak in which v_B and v_C are the two correlated components. Since equal correlations are not observed between the various combinations of components, the character of the oscillations must differ somewhat from the coast to the offshore station. This will be discussed further under seasonal variability, Section 4.2.2.4.

Given that the coastal and offshore winds are highly coherent, it is reasonable to compute transfer functions to account for the portion of variance in common. These are shown in Figure 4-38. Our sets of amplitudes and phases are shown for $H_{u_C u_B}$, $H_{v_C u_B}$, $H_{u_C v_B}$, and $H_{v_C v_B}$ as defined in Section 4.2.2.2. The amplitudes are dimensionless since they represent a ratio of offshore to coastal wind speeds. The phases are in units of radians. Positive values mean that the offshore winds lag the coastal winds. For the purpose of estimating u_B from the coastal wind velocity, recall from the coherency structure that v_C was relatively unimportant. Consequently, the primary transfer function for u_B is $H_{u_C u_B}$, shown in the upper left hand corner. The 90% confidence intervals for random errors were calculated at a periodicity of 100 hours (they vary with frequency as the coherence and energy levels vary and 100 hours was arbitrarily chosen as a midpoint for synoptic weather systems). Within the 90% confidence interval the amplitude lies between 1.3 and 2.3 and the phase at the buoy either lags or leads that at the coast by a small amount (on the average, the offshore winds lag the coastal winds). The small phase difference which is comparable to the size of the random error is due to the fact that the spatial scales of the synoptic weather systems are on the same order as the station separation. The amplitude of $H_{v_B u_B}$ lies between 0 and 1.2 while its phase is indeterminate at the 90% level.

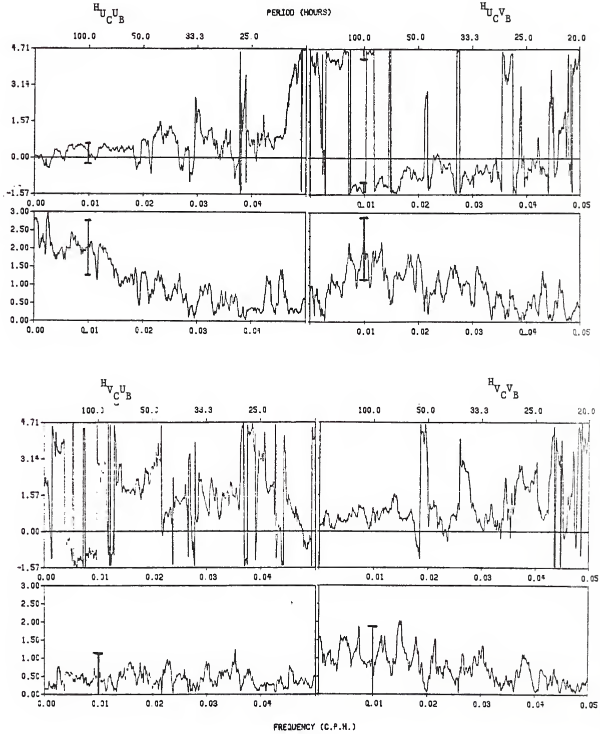


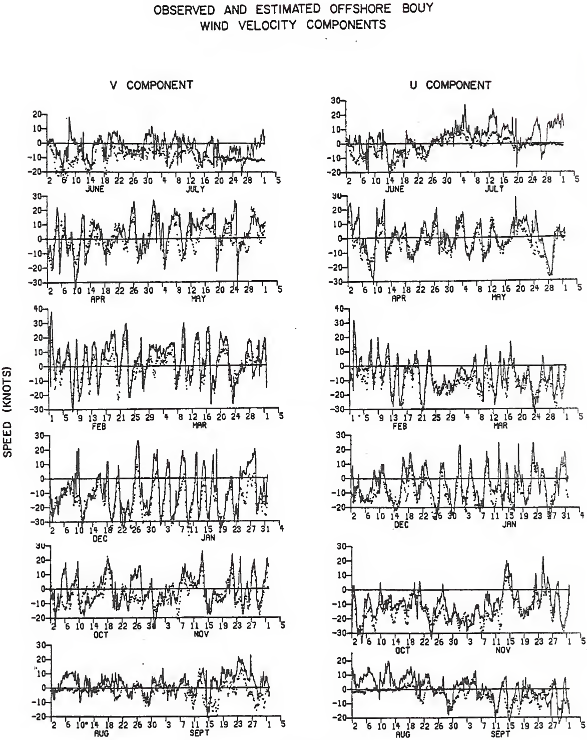
Figure 4-38 Transfer function amplitudes and phases for estimating offshore wind velocity components from coastal wind velocity component. The quantities are defined in the text and the 90% confidence interval with 24 degrees of freedom are shown at the 100 hour periodicity.

For the purposes of estimating v_B from the coastal wind velocity, both u_C and v_C were important. $H_{u_C v_B}$ and $H_{v_C v_B}$ are shown in the upper and lower right hand corners respectively. The amplitude of $H_{u_C v_B}$ at 100 hours lies between 1.2 and 2.9 at the 90% level and the phase varies by a small amount about $\pi/2$. The amplitude of $H_{v_C v_B}$ at 100 hours varies between 0 and 1.9 while its phase is indeterminate. Indeterminate phases at a given confidence interval arise when the random error in amplitude is larger than estimated amplitude. The phase would be determinate (with a relatively small error) at adjacent frequencies or it would be determinate at 100 hours if further frequency averaging were performed to further increase the number of degrees of freedom.

The phases of $H_{u_C u_B}$ and $H_{v_C v_B}$ are similar and slightly positive, i.e., the components at the buoy lag their counterparts at the coast. The phases of $H_{v_C u_B}$ and $H_{u_C v_B}$ are approximately $-\pi/2$ ($+\frac{3\pi}{2}$ is the same as $-\frac{\pi}{2}$). This points out the elliptical nature of the oscillations i.e., the u's and the v's are in quadrature or out of phase by $\pi/2$. This will be discussed in more detail in the next section.

The transfer function amplitudes are similar to the r.m.s. ratios based upon overall variance discussed previously. Increased averaging would make them more stable and recommendations for this will follow after discussion of seasonal variability.

Given the transfer functions, the estimation of offshore winds from coastal winds simply requires a set of two complex multiplications in the frequency domain, a summation, and an inverse Fourier transformation to calculate the estimated time series. The estimated and observed time series are compared in two figures. The first one, Figure 4-39, shows the estimated time series as dots superimposed upon the observed time series as solid lines. With the exception of the beginning and end which were 10% cosine tapered to zero, the agreement between estimated and observed time series is excellent (note that the June and July v component offset is due to a plotter malfunction and is not real). The second one, Figure 4-40 shows a comparison of low pass filtered vector and component representations. Again the agreement is very good, particularly for the winter time synoptic weather systems which propagate offshore.


OBSERVED AND ESTIMATED OFFSHORE BOUY WIND VELOCITY COMPONENTS

V COMPONENT

U COMPONENT

Figure 4- 39 A comparison between observed (solid lines) and estimated (dots) offshore wind velocity component using the transfer functions of Figure 4-36 as described in the text.

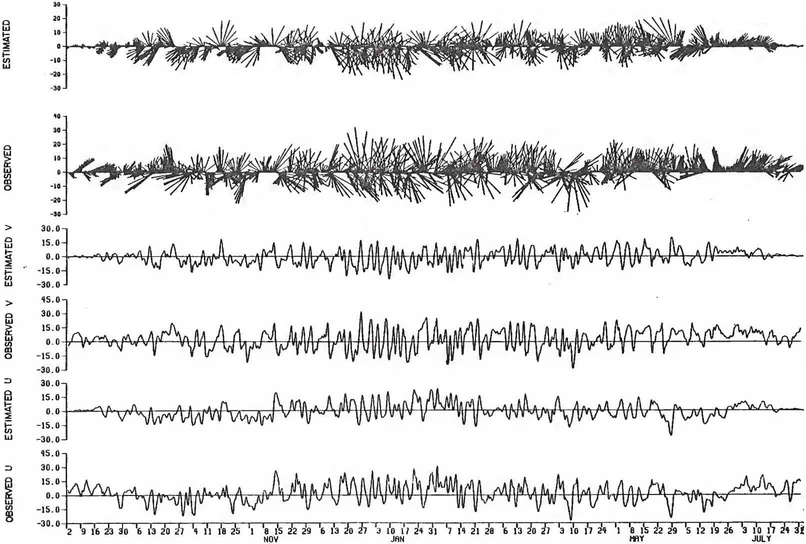


Figure 4-40 A comparison between low pass filtered observed and estimated offshore wind velocity components and vectors using the transfer function of Figure 4-36 as described in the text.

4.2.2.4 Seasonal Variability

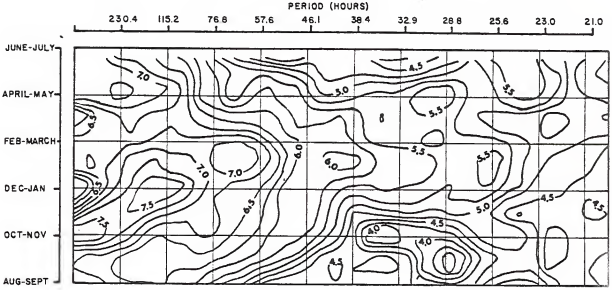
As evident from Figure 4-40, both the coastal and offshore wind velocity vectors change character as a function of season. The purpose of the following section is to investigate this seasonal variability. The coastal and offshore wind velocity time series were broken into 2 months (61 days) overlapping segments beginning with August-September, September-October, October-November and so on. Autospectra, rotary spectra, velocity hodograph parameters, multiple coherence functions, etc., were then computed for each of these 11 segements. The spectral quantities were averaged over a bandwidth of 4.56×10^{-3} c.p.h. for approximately 13 degrees of freedom.

The distribution of kinetic energy density as a function of frequency and time is shown in Figure 4-41 for u_C and v_C. The base 10 logarithms of kinetic energy density for each of the components are contoured at intervals of 0.25. A pronounced ridge appears over the winter season and a trough appears at the summer season. Peaks exist during the winter season at 2 to 5 day periodicities. During the summer, the spectra show a more monotonic decrease in energy density with increasing frequency. The sea breeze phenomenon shows up most clearly in v_C. A ridge appears from August-October at the 24 hour periodicity followed by a trough from November-January followed again by a ridge from January-July. The sea breeze is strongest from March-April and weakest from November-December at Charleston.

Similar distributions for u_B and v_B are shown in Figure 4-42. The ridge during the winter and trough during the summer are even more clear than for the coastal components. The offshore energy levels are uniformly higher than the coastal ones and winter peaks are also observed at synoptic weather system time scales. The summer spectra again show a more monotonic behavior with frequency.

As the wind velocity vector rotates through a cycle, the tip traces over what is defined as a hodograph. In the limit that the velocity vector consists of a single Fourier component, the hodograph would be a well defined ellipse. In reality, the velocity vector consists of a superposition of several random constituents. Averaging over a given bandwidth yields an averaged ellipse which can be described by several parameters. We will now present some of these velocity hodograph ellipse parameters as a function of frequency and time in order to view

LOG U_C KINETIC ENERGY DENSITY as a FUNCTION of FREQUENCY and TIME



LOG V_C KINETIC ENERGY DENSITY as a FUNCTION of FREQUENCY and TIME

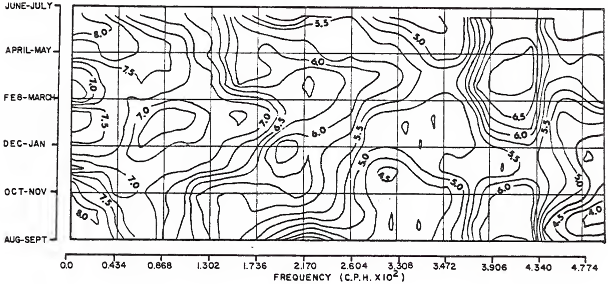
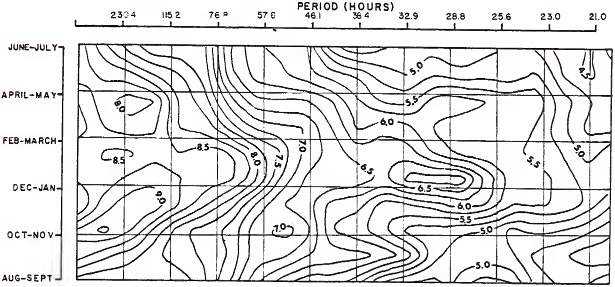


Figure 4-41 A contour plot of the base 10 logarithm of the v and u wind velocity component kinetic energy density spectra as a function of frequency and time at the coast.

LOG U_B KINETIC ENERGY DENSITY as a FUNCTION of FREQUENCY and TIME



LOG V_B KINETIC ENERGY DENSITY as a FUNCTION of FREQUENCY and TIME

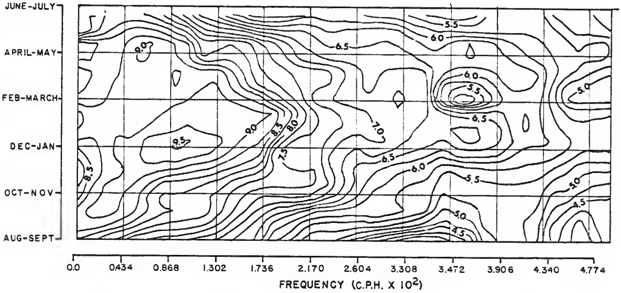


Figure 4-42 A contour plot of the base 10 logarithm of the v and u wind velocity component kinetic energy density spectra as a function of frequency and time at the offshore buoy.

the changing character of the wind fluctuations at the coast and offshore. The parameters to be discussed are the maximum coherence squared, the minimum coherence squared, the ellipse orientation and the ellipse axis ratio.

Coherence squared varies with coordinate rotation. As such, it possesses a maximum and a minimum value. The minimum value occurs between the velocity components measured relative to the principal axis or normal coordinates, i.e., the axes associated with the major and minor axis of variance. The maximum coherence occurs relative to axis rotated 45° from the principal ones. Simultaneously high maximum and minimum coherencies imply coherent elliptical oscillations, i.e., reproducible ellipses without very much scatter; simultaneously high maximum coherence and low minimum coherence imply coherent rectilinear motions; while simultaneously low maximum and minimum coherencies imply incoherent motions, i.e., the hodographs are not reproducible and contain considerable scatter.

An ellipse has a semi-major and a semi-minor axis. The orientation of the ellipse is defined as the angle which the semi-major or principal axis of variance makes with respect to east. It is measured in units of π radians cum sole from east, e.g., 0.5 corresponds to $\pi/2$ or north.

The ratio of the semi-minor to semi-major axes defines the axis ratio. It varies from zero for rectilinear motions to 1.0 for circular motions. The sign of the axis ration gives the polarization of the ellipse. If the axis ratio is negative the polarization is clockwise. If it is positive, the polarization is anti-clockwise.

Figure 4-43 shows these velocity hodograph parameters as a function of frequency and time for the coastal winds. The densely stippled regions for maximum and minimum coherence squared signify values greater than 0.6 which are arbitrarily called high. The lightly stippled regions denote values less than 0.2 which is the approximate 10% significance level. Thus, lightly stippled regions are incoherent.

The winter months at 2-5 day periodicities show equally large maximum and minimum coherence squared at the coast. This region corresponds to the kinetic energy density winter ridges and peaks shown earlier. In this range of large max-

COASTAL STATISTICS

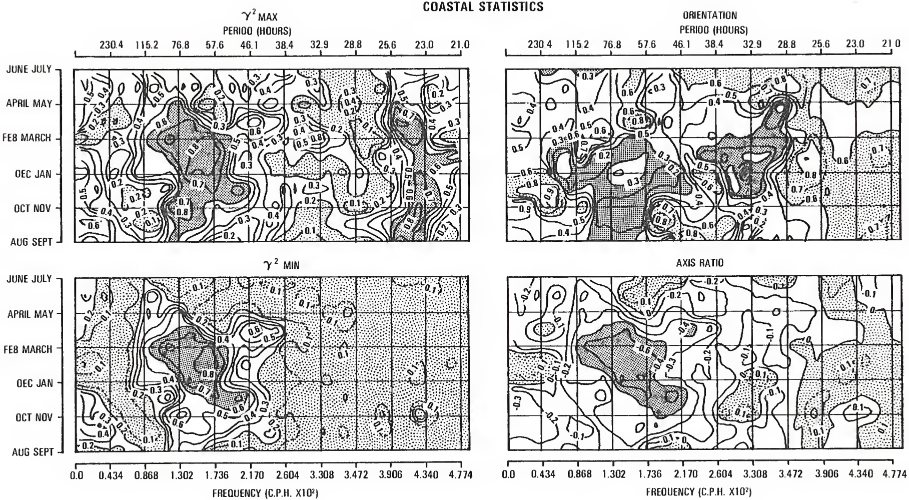


Figure 4-43 Contour plots of the maximum and minimum coherencies squared, and the velocity hodograph ellipse orientation and semi-minor to semi-major axis ratio as functions of frequency and time at the coast. For the coherencies, the dark stippling highlights values greater than 0.6 while the light stippling highlights values less than the 10% significance level of 0.2. For the ratio, dark stippling highlights absolute values above 0.4 while light stippling highlights values greater than zero. For orientation, dark stippling highlights alongshore while light stippling highlights perpendicular to the shoreline.

imum and minimum coherence squared, the wind fluctuations are coherent and elliptical with axis ratios of about 0.4 - 0.6 (darkly stippled regions), clockwise polarizations, and alongshore orientations (darkly stippled regions).

The minimum coherence squared at the coast is nearly zero over most of the remaining frequency, time space. The maximum coherence squared is also greatly reduced with the exception of the sea breeze regime. There the motions are coherent and rectilinear, with axis ratios near zero (values between 0 and 0.1 are lightly stippled), and oriented perpendicular to the coastline (lightly stippled regions). Thus, the most structured or orderly oscillations at the coast occur at synoptic time scales during the winter and at the sea breeze.

A similar set of hodograph parameters are shown in Figure 4-44 as a function of frequency and time for the winds observed at the offshore buoy. High maximum and minimum coherence squared occur during the winter months at synoptic scales. The values are larger than the coastal counterparts and this region of high coherence extends over a larger frequency band and for longer times. The simultaneously high maximum and minimum coherence region has ellipse axis ratios of between 0.5 and 0.6 being slightly more circular than the coastal winds and orientations are approximately north-south. Thus, the wind rotates and broadens upon leaving the coastal influence and the Gulf Stream probably plays a role in the orientation change.

During the summer months, the offshore winds remain fairly coherent (relative to the coastal winds); however, they become more rectilinear and are oriented alongshore. This behavior is clearly evident in the stick plots of Figures 4-33 or 4-40, and it is due to the Bermuda-Azores high which intensifies during the summer.

Thus, the offshore winds are more structured and orderly than the coastal winds. Their bandwidth of high coherence extends over a larger frequency domain and they remain orderly well into the summer months. They are somewhat more circular than the coastal winds and their orientation shifts toward northward during the winter. During the summer the Bermuda-Azores high determines the orientation which is approximately alongshore.

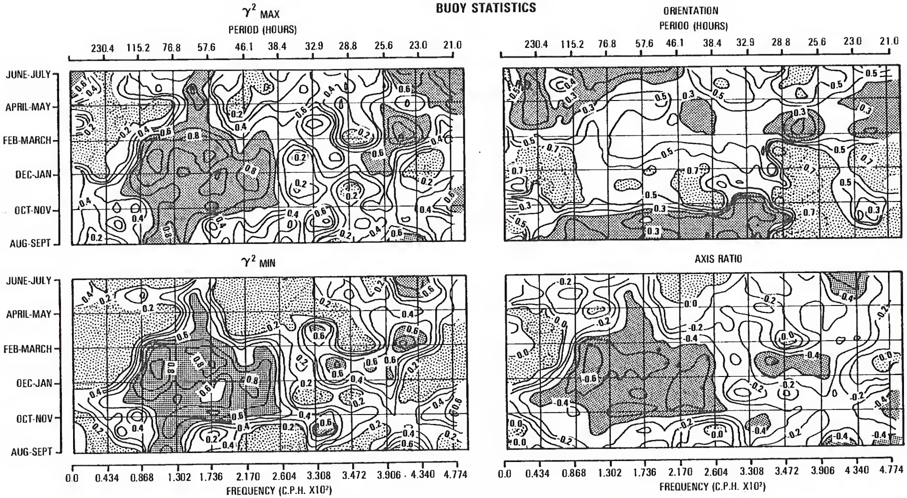


Figure 4-44 Same caption as Figure 4-43 only for the Offshore Buoy.

As a measure of predictability, the multiple squared coherence is plotted as a function of frequency and time in Figure 4-45 for both u_B and v_B. Darkly stippled regions correspond to values greater than 0.8 and lightly stippled regions correspond to values between 0.6 and 0.8. Both are considered as regions of high multiple coherence or regions of good predictability. Values less than 0.6 may be incoherent as that is the approximate 10% significance level. The most predictable regions, of course, are those encompassing the winter season synoptic weather systems. During the winter, predictability extends down to oscillations with time scales of approximately 1.5 days. The predictability during the summer is not as good as during the winter and the overall predictability for u_B is better than for v_B.

4.2.2.5 Recommendations

The results of Section 4.2.2 are very clear. Coastal and offshore winds differ markedly in the SAOS region. Therefore, usage of coastal winds as input to trajectory or circulation models can lead to large systematic errors if account is not given to their offshore changes. However, the offshore and coastal winds are highly correlated and linear mean square estimation provides an operationally feasible way of extrapolating coastal winds to offshore winds. Wind fields could be obtained by a combination of this technique with other objective mapping techniques.

Transfer functions computed from 1 year long records were presented and yielded excellent results. They were not very stable, however, and further refinement should be pursued. The seasonal variability section suggests the avenue for refinement. Winter and summer seasons are sufficiently different that separate transfer functions for the two seasons should be developed. This should result in more stable statistics since one season will not be biased by distinctly different behaviors of the other seasons. Experimentation with the averaging bandwidth should yield optimal estimators. The random errors are a function of coherency and degrees of freedom, both of which vary with averaging. Optimal estimators may be found by increasing the frequency bandwidth until the random error is a minimum. Further increase in bandwidth would cause the coherency to decrease thereby increasing the random error. The fact that the winter synoptic scale bandwidth is large will facilitate the above approach.

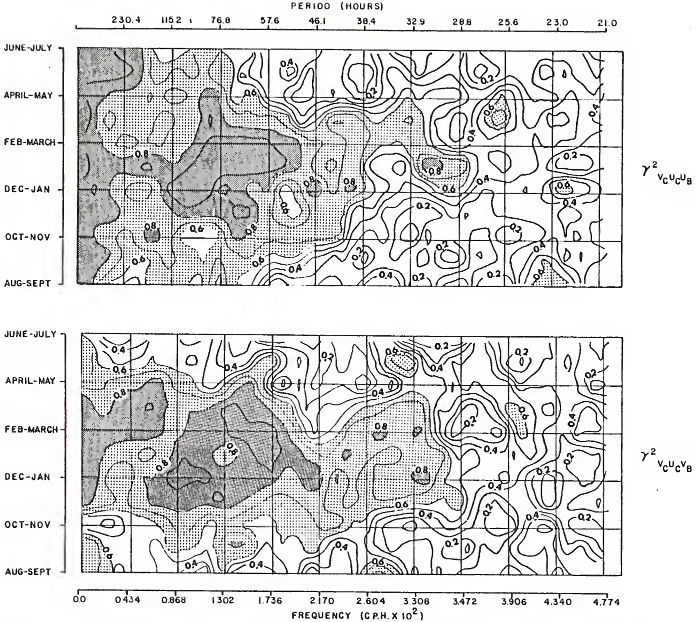


Figure 4-45 The multiple squared coherence as a function of frequency and time between v_B or u_B and the coastal component v_C and u_C. Darkly stippled regions are greater than 0.8, lightly stippled regions are between 0.6 and 0.8, and no stippling indicates region below the 10% significance level of approximately 0.6.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 OVERALL ADEQUACY OF EXISTING MODELS TO MEET BLM OBJECTIVES FOR THE SAOS REGION

Over the past fifteen years considerable effort has been expended in the development of models of ocean circulation. Highly theoretical numerical models, while giving insight into the ocean physics, are not applicable to the BLM's needs in the SAOS region due to the complexity of the flow in this region and the implications thereof on field data requirements to initialize, drive and verify the models. There are five basic findings of the model evaluation study which are encapsulated below.

- With the exception of surface trajectory prediction, adequate models are available to meet the needs of the BLM in diagnostic and prognostic modeling of currents at the surface, in the water column, and in the benthic boundary layer.
- The available data base is generally insufficient to define boundary conditions and initial conditions, or drive the models in any more than a diagnostic mode.
- Field verification is essential for any models used in the SAOS region; the BLM requirements for realism in predictions, and utility of products dictates that the field verification phase be an essential part of any BLM modeling program.
- The special boundary condition imposed by the Gulf Stream and associated spin-off structures is a problem that must be studied in greater detail, and will be difficult to deal with in any model.
- Based on the availability of data and the state of knowledge of circulation over the Blake Plateau, it is not possible at the present

time to model with any reliability the flow at the surface, in the water column, or at the bottom. Although models could be written for the Blake, they would be merely an academic exercise and would be highly speculative.

5.2 RECOMMENDATIONS

The recommendations in the following sections are based on the entire model evaluation including the model evaluation workshop. They were developed on the basis of two important facts: 1) regardless of which models were to be used, they had to be realistic, reliable and achievable within the means (time and money) available to BLM, and, 2) the driving force in the BLM environmental assessment program is the needs of the decisionmaking process; therefore, the models selected must be able to serve those needs. It should be emphasized that all of the recommendations contained herein cannot be fulfilled in a short period of time, but are offered as guidance in short- and long-range studies planning.

5.2.1 Recommendations for Bottom and Sediment Transport Modeling

As stated previously the state-of-the-art in bottom and sediment transport modeling is far in advance of actual field measurements that could be used to verify the models. Models by Weatherly (1977), Adams and Weatherly (1979), Madsen and Grant (1978), and Grant and Madsen (1979) are primary examples of highly sophisticated models based on turbulence closure schemes, and could readily be adopted to the needs of BLM for transport in the benthic boundary layer on any continental shelf. It is, therefore, not our recommendation to develop new and more sophisticated models, but to adapt one of the existing models for benthic boundary layer transport to accommodate specific cases in the SAOS region. Choosing one over the other is almost an academic exercise since they are not substantively different. A major consideration is, however, the fact that the Weatherly model has been computer codified and run for several different real cases. It is essentially de-bugged, and would require transformation to run on BLM hardware and minor modifications to accommodate special conditions.

The real limitation in applicability of bottom and sediment transport models to any region is in the field verification phase and in improvement of input data. At the present time there is no field data to justify the use of a particular skin friction or total shear stress value the selection of which would result in differences ranging up to 1000 percent in the output of a bottom sediment transport model. There are two field experiments planned by the National Science Foundation which could variously improve the reliability of these values, however, the objectives of the programs are not specifically to solve that problem. It is our feeling that it is beyond the scope of the BLM mission to conduct experiments to improve the reliability of these or any other terms in the existing model equations. That is a task that is best left to the NSF, NOAA, or even the USGS using research and development type funds.

The availability of top quality data to drive or verify the models should be a point of greater concern to BLM. There are very few highly reliable values of near bottom currents, let alone simultaneous measurements of short-term high energy flux (such as wave-induced energy) that would result in suspension of sediment and long-term, lower energy mean current type measurements which would actually entrain the sediment and transport it over any distance. In order to provide more meaningful data to serve as input to a bottom sediment transport model, BLM should provide for the collection of these simultaneous data at several locations in the SAOS. These locations should be determined on the basis of most likely locations of possible point source introduction of sediments from a rig since that would provide the most reliable estimates of sediment dispersion in the benthic boundary layer.

It is further recommended that the water column model that is used by capable of providing realistic and verifiable values for water velocity vectors that are essential input to the benthic boundary layer model. The recommended bottom transport models are capable of making fairly sophisticated predictions on the thickness of the benthic boundary layer, volume transport, and sediment transport and are limited primarily by the quality of the input. One extremely important aspect from the BLM point-of-view is the degree of realism in the prediction, which implies model verification in the context of real-world circumstances. Having input from a water column model that does not produce verifiable results will create a situation where the output from the benthic boundary layer model will be that much less reliable. The interaction between these two types of models cannot be overemphasized.

5.2.2 Recommendations for Water Column Modeling

As discussed in the introduction to the water column evaluation, there are two primary limitations on predictive modeling for the SAOS Region: 1) the inability to forecast the fluid boundary conditions; and 2) the instabilties inherent in the Gulf Stream which limit the prediction of the instantaneous location of the main axis and associated spin-off structures, i.e., filaments and eddies. All time dependent models discussed are subject to these limitations. The value of diagnostic models for the SAOS region lies in the fact that they are time independent (steady state) or quasi-time dependent. Because of the lack of available data on the northern and southern boundary conditions and extreme complexity and variabilty of the boundary represented by the Gulf Stream, the output of such models is more reliable, and more easily verifiable, than the prognostic layer or prognostic level models. It should be emphasized again that the more nonlinear the model, the more likely it will be to amplify errors in designation of the boundary conditions (See Section 2.2.1 for further discussion). Hence, it is suggested that BLM pursue the following strategy in an attempt to improve upon current predictive techniques.

Using seasonally averaged hydrographic and boundary data, construct a diagnostic model and run this model with various wind stress patterns. The Hsueh-Peng or the Holland-Hirschman diagnostic models would probably be the most easily adaptable for the determination of the baroclinic portion of the flow field. Resolution on the order of 3 to 5 km grids could be obtained using available information; input to the model grid could best be developed by means of any one of a number of objective analysis schemes (See Section 4.1 for more discussion). Based on the amount and monthly distribution of available data, it is likely that the best temporal resolution that can be obtained for model output will be seasonal values. As a minimum, runs for the summer and winter hydrographic seasons should be performed. To better define the barotropic component of the flow field, the Hsueh-Lee model could be used provided the constraint that longshore derivatives are small compared to cross-shelf derivatives be dropped (see Section 2.2.2 for further discussion).

The Holland-Hirschman model does incorporate nonlinear dynamics, but they keep the density field fixed and integrate the momentum equations through time. The primary problem with this model would be the boundary conditions which have been formulated for a total ocean; these boundary conditions would have to be completely reformulated to take into account three open boundaries and the model resolution would have to be increased.

The Hsueh-Peng model is the most sophisticated of the linear diagnostic models and most nearly approximates the situation in the SAOS Region. It was originally formulated to include three open boundaries and makes only one assumption that is not acceptable for the South Atlantic Bight. If the constraint that alongshore derivatives are small compared to cross-shelf derivatives is dropped, the model can readily be used to determine seasonal variation in the velocity and pressure fields. The boundary conditions of the Hsueh-Peng model are the most realistic, in terms of the South Atlantic Bight, of all the diagnostic models reviewed, and the physics included in the model match the physics of the SAOS. This model has been used in other continental shelf areas (Oregon and the New York Bight) and has produced results which very closely approximate actual field measurements. In addition, the Hsueh-Peng model is up and operating at the North Carolina State University for Onslow Bay and Raleigh Bay of the Carolina Capes area.

Should BLM wish to know the velocity field on a specific day, the diagnostic calculation corresponding to that hydrographic season and wind field can be accessed. Then, VHRR imagery for the day in question could be scanned to determine if any Gulf Stream filaments or eddies are present. If these structures are present a velocity field associated with these features could be added to the diagnostic results to produce the velocity field on the day in question.

Although errors will clearly result from the approach, this is the most cost-effective manner in which BLM could operate. More sophisticated costly modeling approaches, while theoretically more complete, will not result in an improvement in predictive capability because of the inability to verify the output of such models.

Additional field data should be collected on temporal and spatial scales appropriate to the model selected for the purpose of better defining the boundary and initial conditions. With this additional data the model(s) can be advanced from the diagnostic to the prognostic stage. The problem of more carefully defining the Gulf Stream as a boundary condition will also have to be addressed through collection and analysis of additional field data in order to advance the state of modeling circulation in the SAOS region.

Due to the dearth of information available for the Blake Plateau region, any attempt at modeling would be an academic exercise, the result of which would be a purely theoretical model that could be categorized primarily as a "best guess". What can be done for the Blake Plateau, such field measurements should be initiated in fiscal year 1980 so that the modeling effort could go forward with the decisionmaking process.

5.2.3 Recommendations for Surface Trajectory Modeling

Improving upon existing oil spill trajectory models will require an increased understanding of the individual processes governing the oil on the sea surface. Advection and spreading can be categorized as physical proceses, while evaporation and the other non-conservative effects generally lumped under weathering can be categorized as physical-chemical processes. The work of Mackay and Leinonen (1977) and the references cited therein offer a good indication of the time scales involved in the non-conservative engineering approach by neglecting the physical-chemical factors and recognizing the associated safety factor. Thus, it is suggested that the BLM's primary focus should be upon the physical aspects of advection and spreading, and that of those two, advection is the most important since it results in the largest displacement.

The analytical aspects of spreading on a quiescent body of water are fairly well understood. It is the turbulent aspects or the eddy diffusion which complicates the process. Areas requiring further attention are: 1) the differential spreading of the hydrocarbon constituents making up the slick, 2) the mechanisms of tar ball formation, and 3) the role of turbulence in distribution the oil through the mixed layer. The importance of the former is that the lead constituents control the surface tension which limits the analytical aspects of the spreading.

The treatment of advection as the vectorial sum of wind drift, circulation, and tidal currents is an operationally feasible approach. Improvements may be made by modeling each of these three aspects better. Tidal current charts are generally available for nearshore waters. However, tidal current charts are generally not available for the major portion of the SAOS region. The magnitudes of the observed tidal ellipses in the SAOS region are typically 1-3 kilometers. Sufficient data are presently available or will become available over the next two years by way of DOE and BLM supported field work to begin synthesizing a tidal model for the SAOS region. It is recommended that this task be performed. Although it is recognized that advection by tidal currents is generally of lesser importance than the contribution from mean current or wind drift, their near deterministic nature will allow for accurate modeling, thus removing one uncertaintly from the trajectory model calculations. Also, disregarding tidal forces in a trajectory model could lead to serious problems in prediction for shallow areas which are common in the nearshore of the South Atlantic Bight.

Inclusion of the seasonally varying "mean" circulation into a trajectory model has been a severe limitation. This limitation is exemplified by the USGS modeling effort for the mid-Atlantic OCS region (Slack and Wyant, 1978). Depending upon which data set they used, the trajectories were either toward the shore or away from the shore. The reason for this is the large and variable velocity gradient associated with the Gulf Stream. Thus, depending upon initial conditions (the specified mean current field), the oil spill trajectories may be diametrically opposite. Existing models could be improved significantly by calculating seasonal mean currents via a diagnostic hydrodynamical numerical model. Examples of this approach were given by Premack and Brown (1973) for Narragansett Bay, Galt and Pease 1978 for the seasonal circulation in the northeastern Gulf of Alaska, and Miller, et al, (1975) for the New Jersey Coast (not reviewed herein). Though not endorsing any of these models explicitly for usage in the SAOS region, the concept of utilizing a hydrodynamical model in conjunction with a trajectory model is strongly recommended. One step further would be to use a prognostic numerical model to calculate the time varying drift and circulation, but this is probably not feasible at present given the complexities of the SAOS region as discussed in Appendix A of this report.

It is generally accepted that the surface drift caused by the combined effects of wind and waves occurs at some 3 percent of the wind speed, and at an angle of between 0° - 45° to the right of the wind depending upon time scales, water depth and sea state. However, the wind factor and the deflection angles used in any of the models considered here, or in other reviews, may be subject to errors of around a factor of 2. The region of air-sea interaction is not a constant parameter linear system and the mechanisms of air-sea momentum transfer remains one of the more important and neglected areas of physical oceanography. A better understanding of the physics governing air-sea momentum exchange is required to improve our modeling capability. Well conceived field experiments with inclusion of sea state data are necessary to differentiate between the momentum going into currents, waves, mean wave momentum, Langmuir cells, etc.

Attempts at validating or intercomposing existing oil trajectory models with the existing data seems fruitless. An adequate data set for this purpose does not presently exist. Drifter experiments are recommended. These experiments would involve an ensemble of releases from one or several stations with each member (a collection of drifters) of the ensemble (the sum total of repeated drifter releases) tracked for a period of 10 days to several weeks. This would allow for a statistical treatment of drift data at time scales similar to landfall estimates and synoptic weather systems. The data could be used for eventual model verification studies. Seasonal variability would be expected, and an experiment should be performed accordingly over the course of at least one year. Results from Lagrangrian experiments could be compared with results from Eulerian transfer functions derived directly from data or indirectly from sophisticated numerical models. The intercomparison of the two results (Eulerian and Lagrangian) would provide a realistic indicator of predicitve capabilities.

Given that the air-sea momentum exchange could be modeled accurately, the ensueing results would still be limited by the quality and quantity of meteorological data, primarily wind velocity. It has been customary to use coastal meterological data for wind velocity time series or probabilistic transition matrices. Though synoptic weather systems have coherence scales on the order of 100 kilometers or more, the amplitudes and spatial characteristics of the winds over the coast and at sea may differ considerably. This was discussed in detail for a portion of the SAOS Region in Section 4.2. Improving the meteorological data base is highly recommended. Incorporation of offshore buoys into the BLM SAOS studies is an important first step. Statistical and analytical tools can be used to extrapolate and interpolate the fields. In the case of the SAOS Region, errors on the order of 400% occur using coastal wind data alone.

An increased sea state data analysis is also important. Should the Huang (1979) work prove correct, then sea state (mean wave slope) would play a major role in trajectory modeling.

In summary, priority should be given to improving the advection portion of oil spill trajectory models. This necessitates improving our knowledge of tidal, seasonal mean currents, and air-sea momentum exchanges. The tidal current problem could be solved most easily since it is largely deterministic, and data are available for synthesizing a barotropic tidal model of the SAOS region. A marked improvement in seasonal mean currents input data (over drifter bottle data presently used) could be realized by incorporating a diagnostic hydrodynamical numerical model into trajectory models. Improving our understanding of the air-sea momentum exchange will require well designed field experimentation with due regard to sea state. Wind drift and waves are certainly not independent as shown by recent observational work, e.g., Lange and Hufnerfuss (1978), and Hufnerfuss (1978), and by recent theoretical work on Langmuir circulations, i.e., Garrett (1976). Paralleling all of the above with the exception of the tides is a need for improved at-sea meteorological coverage along with statistical means for extrapolating and interpolating the fields.

Finally, due regard must also be given to smallerscale spatial processes which can be very important. For example: 1) Langmuir cells, common ubiquitous features of the sea surface, are capable of causing channel slicks downwelling, and mixing of oil throughout the upper mixed layer, 2) Coastal riverine fronts can cause blocking and sinking, and 3) Gulf Stream intrusions and meanders can largely alter the "mean" circulation.

5.2.4 Recommendations for Ocean-Structure Interaction Modeling

Although our analysis of ocean-structure interaction modeling was more of a literature review and summation than a qualitative-quantitative analysis, certain recommendations can be gleaned from the review and the model evaluation workshop deliberations.

Since wave forces are known to produce the most stress on OCS structures, emphasis should be placed on development of a suitable wave hindcasting model to provide input to an ocean-structure interaction model. This latter model could then provide significant information for the risk assessment phase of the OCS decisionmaking process and the post-leasing decisions related to exploration and development permitting. Related to this is the need for additional directional wave spectra, and a better understanding of the wave-sediment interactions on a compliant bottom. Some advances in this latter area have been made by the USGS-Corpus Christi Office of Marine Geology in their Delta Front Sediment Stability Project, and there is a recent study funded by Sea Grant to examine wave energy attenuation due to bottom friction.

The whole topic of current-structure interaction (particularly storm-generated currents) is one that has been poorly studied. Due to the severity and frequency of storms in the SAOS region and due to the presence of the Gulf Stream and related spin-off structures, additional work must be done in the understanding of generation, propagation, and duration of such currents, and the means by which they can be accommodated in ocean-structure interaction models. Also the synergistic effect of storm-generated waves and currents, and the Gulf Stream should be further studied.

In the future, specific emphasis should be placed on the interaction of pipelines and the physical forces acting on them as well as the bottom sediment-pipeline interactions. This topic has not received sufficient attention to data and could provide essential information for advancing the comprehensiveness of risk analyses performed by the BLM and USGS.

APPENDIX A

GEOSPECIFIC ASPECTS OF THE SOUTH ATLANTIC OCS REGION

A.1 GEOSPECIFIC ASPECTS OF THE SOUTH ATLANTIC OCS REGION[1]

By L. J. Pietrafesa, NC State University and JAYCOR

A.1.1 The Role of the Gulf Stream

The influence of the western boundary current, the Gulf Stream, which persists generally along the seaward edge of the continental margin between Capes Hatteras and Canaveral, may be considerable in terms of physical, chemical and biological aspects of the oceanography of the South Atlantic Bight. Recent continental shelf studies (DOE and BLM) in the Carolina Capes and Georgia Bight Region have yielded much valuable information to date in establishing a more complete understanding of the dynamics and influence of the Gulf Stream, which to date, has been lacking in terms of being spatially and temporally synoptic. It is of use to briefly review some of our understanding of the Gulf Stream influence, and then to proceed in an overview analysis of how our present studies have served to either reinforce, modify, re-explain or describe anew the phenomenology of the Gulf Stream influence, specifically of Gulf Stream frontal events on the shelf waters of the South Atlantic Bight.

Very High Resolution Radiometer (VHRR) data from satellites has produced imagery in the visible channel over a major portion of the coastal waters off the eastern seaboard of the United States. These satellite images (Legeckis, 1975; Stumpf and Rao, 1975) suggest that filaments and cold dome eddy pools evolve from growing wavelike instabilities which may initially be wind induced (See Figure A-1). The filaments manifest themselves as warm, southward-oriented, tongue-like extrusions of Florida Current water onto the shelf, similar to the shingle structure observed by Von Arx, Bumpus and Richardson (1955). In the Florida Straits they are confined by the narrow shelf coastal boundary, and observed diameters range from 10 to 30 km. Filament vertical extent is approximately 200 m. Lee (1975) concludes that these features, variously referred to as spin-off eddies, are a dominant mechanism for shelf water mass exchange off southeast Florida and estimates the shelf residence time as one week due to eddy water renewal.

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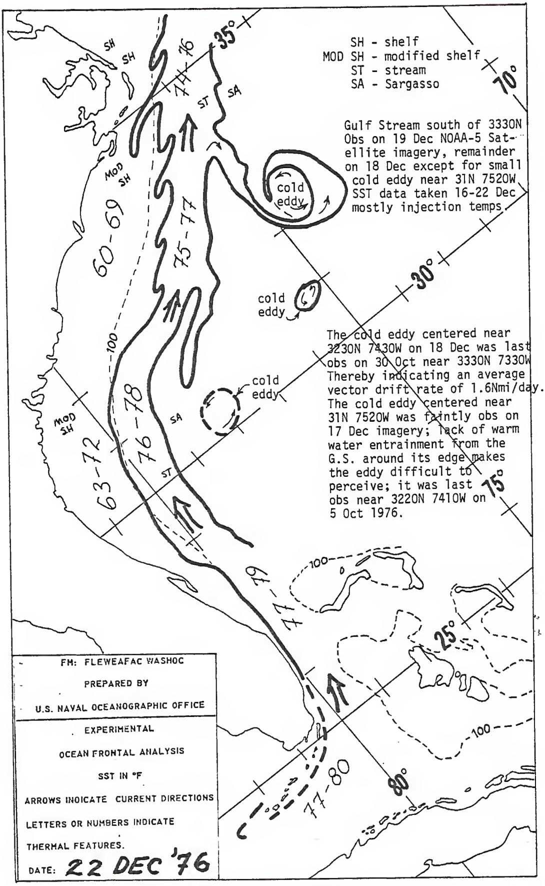
[1] Excerpted from a draft chapter prepared for the Final Report of the JAYCOR South Atlantic OCS Model Assessment Program Workshop sponsored by the DOI/BLM and published in July 1979.



SH - shelf
MOD SH - modified shelf
ST - stream
SA - Sargasso

Gulf Stream south of 3330N Obs on 19 Dec NOAA-5 Satellite imagery, remainder on 18 Dec except for small cold eddy near 31N 7520W SST data taken 16-22 Dec mostly injection temps.

The cold eddy centered near 3230N 7430W on 18 Dec was last obs on 30 Oct near 3330N 7330W Thereby indicating an average vector drift rate of 1.6Nmi/day. The cold eddy centered near 31N 7520W was faintly obs on 17 Dec imagery; lack of warm water entrainment from the G.S. around its edge makes the eddy difficult to perceive; it was last obs near 3220N 7410W on 5 Oct 1976.

FM: FLEWEAFAC WASHOC
PREPARED BY
U.S. NAVAL OCEANOGRAPHIC OFFICE

EXPERIMENTAL
OCEAN FRONTAL ANALYSIS
SST IN °F
ARROWS INDICATE CURRENT DIRECTIONS
LETTERS OR NUMBERS INDICATE
THERMAL FEATURES.
DATE: 22 DEC '76

Figure A-1. Map of the Gulf Stream Showing Eddys and Filaments. Drawn primarily from VHRR and SST Data.

Atkinson, et al. (1977) and Blanton and Pietrafesa (1978) have essentially concluded that the similar flushing mechanism is at work throughout the whole of the South Atlantic Bight. Satellite images show that filament-like incursions are a consistent feature along the continental margin of the Carolina Capes region of the SAB.

Flushing frequency is thought to tie directly to the frequency with which meanders and filament events occur. Available information shows that meanders and filament events occur at frequencies betwen 0.1 and 0.2 cycles per day, figures which embrace the pioneering study by Webster (1961), as well as studies reported by Pietrafesa (1979) and Lee (1979). We should point out that previous studies did not unambiguously link onshore/offshore flow cycles on the North Carolina Shelf with meanders or accelerations of the Gulf Stream. From these data, it is obvious that large amplitude current fluctuations, as shown in Figure A-2, with periods ranging from several days to several weeks are common features on the outer continental shelf throughout the SAB.

While it has long been known that the Gulf Stream meanders laterally along the whole of the South Atlantic Bight (the continental margin between Capes Canaveral and Hatteras), a quasi-permanent deflection of the Gulf Stream has recently been postulated offshore of Charleston, South Carolina (Pietrafesa, Atkinson and Blanton, 1978). These authors used hydrographic data, nutrient data and remotely sensed imagery of the sea surface topography and temperature to support their supposition.

Hydrographic and nutrient dta (Atkinson, 1975; Mathews and Pashuk, 1977) indicate that the Gulf Stream Front (GSF) is farther offshore from the shelf break of Charleston than at any other site in the Georgia Bight. Similar data collected in the Carolina Capes region (Atkinson, et al., 1976; Singer, et al., 1977) extend this supposition to Cape Lookout, NC. Additionally, Very High Resolution Radometer (VHRR) and Radar Altimeter (RA) satellite imagery consistently show an eastward deflection of the western GSF, the entire surface thermal expression of the stream, and the axis of maximum sea surface slope, which is related to the axis of maximum surface current (Pietrafesa, Atkinson and Blanton, 1978).

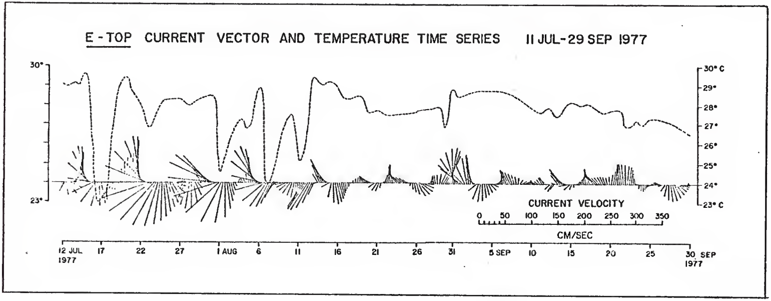


Figure A-2 Current Vector Diagram Showing Passage of a Spin-Off Eddy Attached to a Gulf Stream Meander (Pietrafesa, 1979)

Pietrafesa, Atkinson and Blanton (1978), using twenty-four months of weekly Ocean Frontal Analysis maps for May 1976 to May 1978 (Naval Oceanographic Office), made estimates of: (1) spatial location of any marked seaward deflection of the GSF between Savannah, Georgia, and Cape Fear, North Carolina; and (2) spatial magnitude of deflection of the Stream away from the 200 m isobath Although the GSF is often less clearly defined on these charts, especially during summer, the nearly 100 charts studied reveal a rather consistent point of seaward deflection of the GSF at about 32° N, 79° W. The offshore deflection of the GSF from the 200 m isobath usually falls in the range of 60 to 100 km. These authors also used satellite radar altimetry data to estimate the location of the maximum current axis by directly measuring the surface height, and thus the slope, of the ocean surface. Such data indicated a seaward deflection of the surface height gradient at 32° N, 79° W. From simple geostrophy, this infers a like deflection of the axis of maximum surface current. Several investigators have speculated that this quasi-permanent deflection is related to an irregularity in ocean bottom topography along the outer continental shelf at the Charleston latitude. This bathymetric feature is part of the Blake Plateau, but the pronounced rise shown by the 100 m isobath is known locally as the Charleston Bump. We propose that this feature is responsible not only for the offshore deflection of the Stream, but also for generation of lee waves (Topographic Rossby Waves) which have been observed in the area. These waves apparently emanate from the approximate site of the Rise and are advected downstream toward Cape Hatteras with wavelengths of about 100 to 200 km and phase speeds of about 25 to 75 km/day (Legeckis, 1975).

Recently, several investigators have addressed the physics involved in deflection of the Stream and generation of Topographic Rossby Waves; resulting mathematical models lend theoretical justification to the observational evidence. A simple model of a barotropic jet passing over a bathymetric rise on a regular slope is presented by Rooney, Janowitz and Pietrafesa (1978).

The model, which considers flow over an idealized triangular wedge sitting atop a linearly sloping continental slope suggests a bathymetrically induced deflection just downstream from the bathymetric irregularity. The meander is apparently a damped Topographic Rossby Wave (TRW) which decays in the downstream direction as the square root of the inverse radial distance from the site of the wedge. The wavelength of the TRW is approximately 154 km, and the offshore deflection is approximately 102 km. These waves may contribute to observed GSF meander and filament/eddy events both downstream and upstream of the "bump".

Since filament/eddy and meander events occur along the whole of the SAB, it is clear that there are many possible causes of their generation and modification ranging from the basic nature of time dependent, horizontally and vertically sheared baroclinic jet to the influences of local winds and topography on the jet as discussed by Pietrafesa (1979).

As the filament/eddies advect onto the shelf and develop, during Spring, Summer and Fall, a doming-up of isotherms occurs between the warm filament and the Gulf Stream Front as demonstrated in Figure A-3. This domed-up region indicates an apparent geostrophic tendency and the core of the event becomes cold relative to adjacent, resident shelf waters. For a more definitive example of this process, the reader is referred to Atkinson's (1979) recent hydrographic description of a filament/eddy event mapped in the Georgia Bight in April, 1977. During the wintertime the shelf waters are relatively cold, and while the filament/eddy itself may undergo a process similar to that at other times of the year, its net effect on the dynamics of the shelf may be entirely different from those incurred during other times of the year.

Pietrafesa (1979) estimates, for the Carolina Capes, the numbers of filament/eddies present, by amount, per bay. The features referred to as "eddies" may have been large amplitude or growing meanders; no attempts were made to discriminate or delineate between a large amplitude meander and a filament/eddy (FEE), if in fact there is a difference. Whenever a FEE feature overlapped two bays, each bay was given partial credit for the eddy. The figures can be somewhat misleading in that on consecutive weeks, a particular FEE may persist locally and thus be counted twice or advect along the shore and appear in two different bays. Nonetheless, the point remains that the feature is present and is presumably affecting the ecosystem of the shelf. Pietrafesa (1979) indicated that approximately 35 FEE features are present per bay per year in the Carolina Capes. If one takes this figure at face value, then one can speculate on a FEE being present in a bay every 10 days. Alternatively, if one assumes that some fraction (say, one-half) of these events were the same event counted twice, over a two week period, then one could modestly speculate that a new FEE is present every 20 days

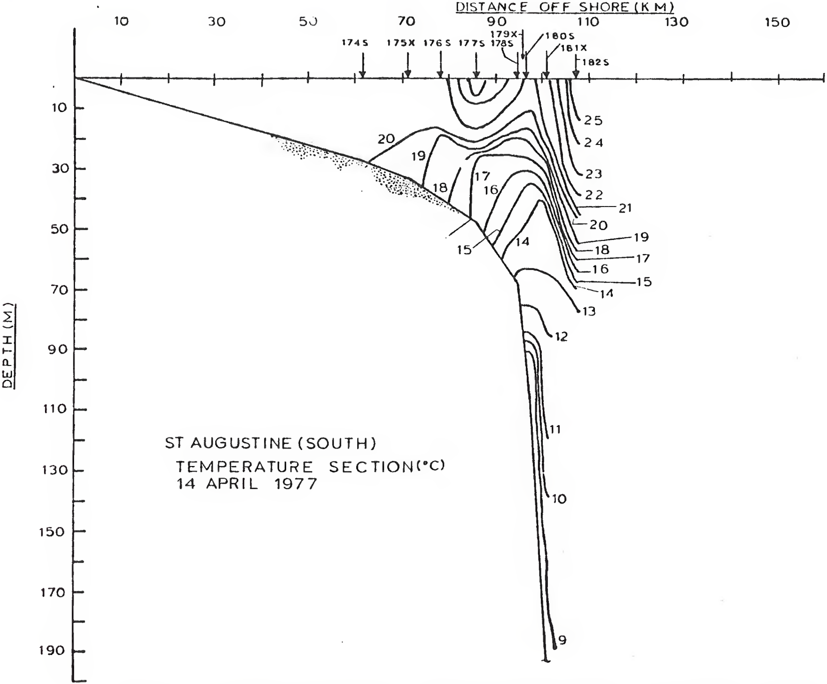


Figure A-3 Temperature Section St. Augustine South 14 April 1977 (Atkinson, 1979) in a bay. It seems fair to speculate that features appear on the order of at least 1 filament event per 20 days per bay and are evident on the order of 1 event per 10 days per bay. It would be of use to modelers to adopt a technique similar to the one used by Halliwell and Mooers (1979) for the mid-Atlantic Bight for mapping the location of Gulf Stream filaments and eddies and for determining the frequency, size and persistence of those structures. Basically, this involves objective mapping of the existing data base (primarily remote sensing data) subject to reasonable dynamic constraints. An alternative approach would be to use a time dependent diagnostic model in which random events such as filaments and eddies are treated stochastically. Because of the great expense and computer capability limitations of the latter, the former approach holds the greatest promise over the next three to five years of providing the necessary input data to the Gulf Stream boundary condition.

The lateral meandering of the Gulf Stream appears to penetrate farther onto the shelf in Raleigh and Onslow Bays than it does in the Georgia Bight. This may be due to the fact that the whole of the continental margin narrows from Jacksonville, Florida to Cape Hatteras. Pietrafesa (1979) presented representative examples of the Gulf Stream meandering current and temperature signature in Raleigh Bay as observed 17 m below the surface in 45 m of water in the southern portion of the bay. He saw an apparent wave like motion with a period of approximately 3-5 days and with cyclonic rotation of the velocity vector. Temperature rises as v increases and drops identically in phase with v. This same meandering feature is evident along the 45 m isobath in Onslow Bay in data presented by Pietrafesa, et al (1978), but is even more dramatically evident in 75 m mooring data from Onslow Bay. Not only are the v and T data from two 75 m moorings located 85 km apart almost totally visually coherent, but the southerly mooring leads the northerly one by approximately a day, and, given the 85 km separation distance, implies a northerly propagation of 3-5 day meandering events of 50 $cm.sec^{-1}$. If the meandering features are viewed as propagating waves, then the phase speed of these northerly propagating features are approximately 50 $cm.sec^{-1}$ (1kt).

On the Georgia Outer Shelf, Lee (1978), and in the Carolina Capes, Pietrafesa (1978) both see energetic broad-banded spectrum peaks at periods of around 2.5, 3.5, 5 and 10 days occurring in the time series from the shelf break, mid-shelf, and winds (Figure A-4). At the shelf break, fluctuations of u, v, and T showed significant coherence at the 95% level for these periods with u leading v by about 90° in phase, which is indicative of organized progressive wave motion. Cross-spectra of time series from current meters located along the shelf break on the Georgia Shelf indicate that perturbations with these periods propagated to the north in the upper layer and they can travel either north or south in the lower layer.

Lee found that fluctuations with 9-12 day periods were highly coherent in v and in T and significantly correlated in u over the 42 km separation in the upper layer along the shelf break. Wave properties suggest that these deviations were produced by long waves traveling to the north at about 40 to 115 $cm.sec^{-1}$ and wavelengths of 400 to 1000 km. Lee's results are less clear in the lower layer for the 9-12 day period motions, giving contradictory propagation directions between different current meter locations. Disturbances with 5-day periods were found to be highly coherent in u and in T along the shelf break (maximum separation was 50 km), but not in v. The u and t information indicates that they traveled to the north in both layers at about 30 to 90 $cm.sec^{-1}$ wavelengths of 140 to 370 km. Perturbations occurring around 3.5 day periods were coherent on both u- and v- components and in T over 40 km separations in the upper layer, which could be explained by northward traveling waves with phase speeds of 100 to 200 $cm.sec^{-1}$ and length of 300 to 600 km. In the lower layer, coherence was weaker, and northward or southward traveling waves are indicated. At the 2.5 day period, fluctuations were coherent in u and T over the 40 km shelf break separation in the upper layer. Northward propagation is indicated at speeds of 100 to 150 $cm.sec^{-1}$ and wavelengths of 200 to 300 km. Modulations of the v-component were not coherent over these downstream distances in either layer. In the near-bottom layer only the u component showed significant coherence at the 2.5 day period, which degraded at 50 km separation.

The finding of southward propagating disturbances in the near-bottom layer and northward in the upper layer by Lee (1979) suggests the possible existence of shelf waves, which tend to trap vorticity along the slope and travel to the south in the absence of a strong northward mean current. Near the bottom, currents are weak and the disturbances are free to travel south; however, in the upper layer the strong flow of the Gulf Stream advects the waves toward the

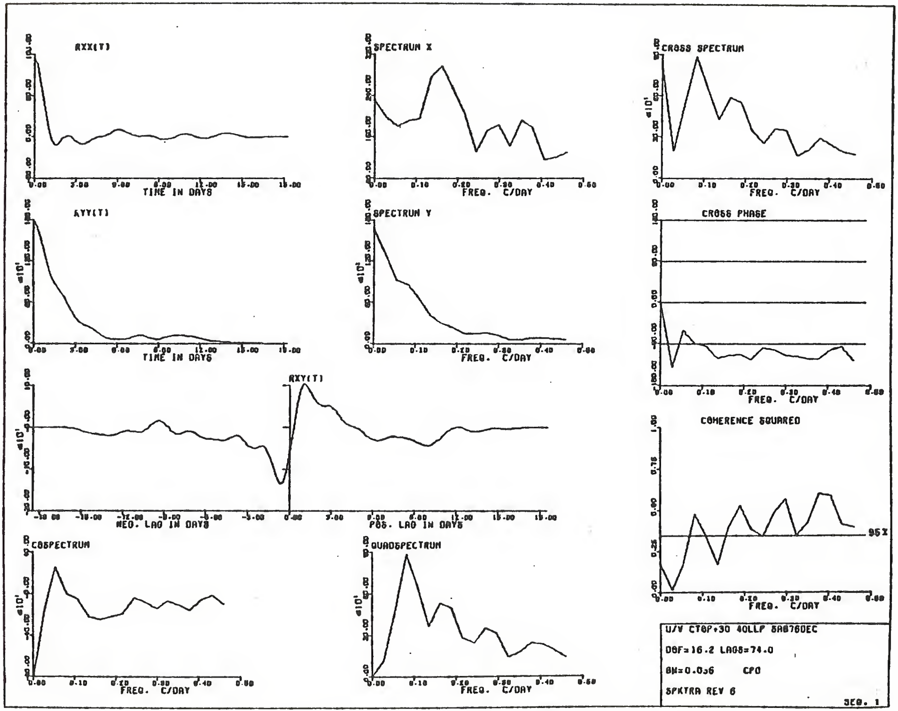


Figure A-4 Cross-Spectra of u and v Components, 40 HLP Time Series From CT, "Winter 76/77" Box Array (Lee, 1979) north. Further complications arise due to the large horizontal and vertical shear at the Gulf Stream front which can cause the perturbations to be unstable and nonlinear. These effects combined with the fact that the current meters had different record lengths could account for the wide range of linear wave properties computed along the shelf break.

In the data sets of both Lee and Pietrafesa, cross-spectra of u against T reveal strong coherence at period of 2.5, 5 and 10 days in both the upper and lower layers at the shelf break with u leading by about 90° in phase. In the upper layer the cospectra is negative at these periods indicating a flux of heat from the Gulf Stream to the shelf. Near the bottom, the u'T' cospectra is positive at the most coherent periods of 5 and 10 days, which indicates a westward transport of cold Gulf Stream anomalies onto the shelf. The cospectra is negative at the 2.5 day period, which suggests there was a flux of heat to the shelf at that period. In the alongshelf direction there was a large downstream transport of heat associated with coherent v'T' fluctuations at 2-3, 3.5-5, and 8-12 day periods.

A.1.2 Meteorological Forcing, Coastal Sea Level and Implications for Currents on the Shelf

The atmospheric climate overlying the South Atlantic Bight is determined by both polar and tropical marine air masses, resulting in a "temperate-rainy" climate with mild winters, long hot summers, and adequate moisture in all seasons, according to Koppen (see Petterson), (1969). The north-south surface temperature gradient over the eastern US reaches a seasonal maximum in late winter of approximately 1.5°C per degree latitude, which is about four times the summer gradient. The polar front, the actual zone of maximum temperature contrast which separates the colder continental air from the warmer, more moist tropical air, both intensifies and shifts southward in the winter to near Cape Hatteras resulting in a region of intense cyclogenesis stretching along the eastern US seaboard from Florida towards northern Europe. Most of the intense extratropical lows develop over the southeast US, but show their greatest growth as the storms move offshore over the warmer ocean, especially in the neighborhood of the Gulf Stream. The mean speed of these synoptic-scale cyclones in 5 to 7 $m.sec^{-1}$ (10 to 15 kt), with less than 20% of the storms moving at speeds greater than 12.5 $m.sec^{-1}$ (25 kt) (NOAA, 1970).

These wintertime extratropical cyclones (and to a lesser extent, the accomanying anticyclones) can affect the coastal oceanic circulation in a number of direct and indirect ways. The surface pressure and wind stress patterns for a mature low can be coherent over 600 km, can persist for three to four days, and can directly drive a large-scale coastal current. Intense lows are frequently accompanied by trailing outbreaks of very cold polar air, causing sharp cold fronts which move southeastward over the southeastern states; and they can bring freezing weather and strong winds as far south as Florida. Smaller scale waves can develop along the polar front near the southeastern coast which exhibit highly variable stress and precipitation patterns on the subsynoptic (10-100 km) scale (Bosart, Vando and Helsdon, 1972; Bosart, 1973). Bosart and Cussen (1973) have found surface pressure fluctuations of 4 to 5 mb amplitude along the coast and have attributed these perturbations to atmospheric gravity wave generation by accompanying frontogenesis. Perhaps the most intense atmospheric pressure and surface wind stress patterns associated with the large scale tropical storms and hurricanes which develop primarily in August-October and occasionally migrate along the Southeast coast, visiting the Carolina Coast with a frequency of about one severe storm every two years (US Navy, 1970). The meteorological forcing on the SAB is thus dominated in winter by transient extratropical storms with considerable variability in strength, structure and persistence of the important meteorological fields. The predominant winds are northwesterly to northeasterly, with some 30% of the observed speeds reported to NOAA (1970) exceeding 8 $m.sec^{-1}$ (16 kt).

The summer meteorological regime along the SAB is controlled by combined processes of rapid weakening of the polar front and an intensification of the Azores-Bermuda High. The region of most intense cyclogenesis has shifted north of Cape Hatteras and while some active frontogenesis and cyclogenesis continues over the southeast US shelf, the atmospheric variability there is decreased in summer. The predominant winds are lighter and southerly to southwesterly. Some 60% of the NOAA-collected surface observations (NOAA 1970) indicate wind speeds of less than 5 $m.sec^{-1}$ (10kt), while 15% indicate wind speeds greater than 8 $m.sec^{-1}$

(16 kt). The standard deviation of the surface pressure shows both a strong seasonal fluctuation and a steady decrease with decreasing latitude south of Cape Hatteras (US Navy, 1970). The standard deviation of the surface pressure at Charleston, SC is about one-half its mean winter value of 7 mb. Ward (1925) and his more recent co-workers suggest that a transition from a northern cyclonic-controlled climate to a more Gulf-like climate with higher temperatures and less dramatic weather occurs along the southeast shelf near the latitude of Charleston.

The recent work of Saunders (1977) suggests that there is a great deal of offshore as well as alongshore structure to the mean wind fields which gives rise to the need for meteorological buoys which would allow for an assessment of the curl and divergence of the wind field as well as a mass and heat air/sea interaction evaluation. Saunders also points out an offshore wind stress maximum which occurs during early fall; he finds no apparent reason for this, but it seems likely that the air-sea temperature gradients may be largest during this time of the year, thereby increasing the drag coefficient and subsequently the relative stress field.

On localized scales, an appreciable diurnal sea/land breeze, as well as an apparent semi-diurnal harmonic thereof, is in evidence along the North Carolina Coast (Pietrafesa, et al, 1978) and is evident at Charleston as well.

We now consider the work of Pietrafesa, et al, (1978) for some further insights into the relationship between sea level and coastal meteorology at Charleston. These authors showed that 40 hour low passed (low-low) filtered atmospheric pressure time series indicates that the SAV, CHS, WIL, and HAT* stations are well correlated over most of the large and even small amplitude variations which is indicative of the high degree of horizontal coherence over length scales of the pressure field much greater than the SAV-HAT radial separation distance which is 620 km. The large horizontal coherence distance presumably reflects the synoptic meteorological scales associated with mid-latitude atmospheric disturbances, especially during the fall, winter and spring periods. The alongshore wind stress components also show essential correlation over the SAV-HAT separation distance, but variations in intensity and structure between stations are more apparent than in the pressure time series. Vector representations or stacks of stick diagrams, of the wind stress during passage of such an event over the station(s). Here it is noted that HAT typically shows the largest stress magnitudes. Alongshore winds tend to dominate both in magnitude and duration relative to the cross-shelf components. Wind stress reversals, noted at all of the met stations, occurred on time scales of several days to several weeks, which are the typical periods of forcing within the atmospheric stress continuum.

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*SAV = Savannah, CHS = Charleston, WIL = Wilmington, HAT = Hatteras

Kinetic energy density (KED) spectra of alongshelf and transshelf wind components at CHS (Pietrafesa, et al, 1978) indicate that within the temporal period of 2 to 14 days, there is a rise in the energy density as approximately the frequency to the minus three halves power, which is consistent with the findings of Oort and Taylor (1969) and Cragg and Sturges (1974) for other coastal regions and is attributed to the passages of cyclones and anticyclones. The KED curve flattens out at periods in excess of 14 days. Within the temporal ranges of interest of the BLM continental shelf study, the range from the order of several days to a month, alongshore winds show a remarkably high degree of visual correlation, save for occasional several day departures, in the various station time series. One can observe similarly good visual correlation between transshelf wind components between station pairs over the whole of the radial separation distance with occasional departures, in the same figure series as above. Over the entire frequency range of 0.5-0.95 cpd, alongshore winds are more energetic than cross-shelf winds. There was a decrease in coherency between station pairs at a rate of 0.1 per 150 km increase in radial station pair distance. Pietrafesa, et al, (1978) thus concluded that winds recorded at any one of the coastal stations could, at least qualitatively, be representative of the wind fields at any of the other stations, located on the order of one to two hundred kilometers apart, with appropriate reservation. The adequacy of representation is an event-, season-, and location-sensitive variables, but for events within the frequency band 0.3 to 0.05 cpd the contention is not without evidential basis. What is suggested herein is that the divergence of the alongshore wind stress may not be large, and furthermore that possibly the curl of the cross-shore wind stress may not be large, but the data indicates little of a definitive nature about the curl of t(x) and moreover nothing about the offshore wind field structure, which is the actual mechanical forcing function.

In the Pietrafesa, et al, (1978a) report, forty hours low-passed atmospheric pressure analyzed from the meteorological stations indicated a high degree of coherence with daily pressures rarely differing by more than several millibars between stations. The phase shifts are nearly zero at all frequencies except for shifts of the order of 0 to 20 degrees over radial distances on the order of 100 to 650 kms with the southerly meteorological stations typically leading the more northerly stations for the entire separate series lengths of 1974 and 1975. It certainly appears from the cross-correlations between station pairs that the pressure spectrum at any individual station is reasonably representative of that at any other with minor adjustments in phase as a function of the pairing and the frequency. Coherence squared (C^2) is typically in excess of 0.9 over station radial separation distances the order of 200 km and drops off from 0.95 to 0.5 at distances in excess of 400 km in the 0.1-0.5 cpd band.

Among factors which significatnly affect sea level, particular note in the Pietrafeasa, et al, (1978a) report was made to the variations in atmospheric pressure, atmospheric winds, oceanic currents and long, shelf wave phenomena. The response of the level of the sea surface to varying atmospheric pressure is more correctly expressed in terms of a frequency dependent barometric factor, i.e., a transfer function for the pressure and sea level system. Herein, the sea level data was "adjusted" (as well as left "unadjusted") for the so-called "barometric effect." For frequencies below 1 cpd, the sea surface responds to changes in atmospheric pressure in a reasonably regular, nearly instantaneous fashion. The adjustment suggested over nearly the entire frequency range of interest in this study (Mysak and Hamon, 1969) for sea level fluctuations due to varying barometric pressure is about 1.0 cm/mbar, i.e., a millibar increase (decrease) in pressure depresses (elevates) the sea surface approximately 1 centimetre.

Remarkably high C^2 results between sea level and alongshore winds, especially at frequencies below 0.35 cpd, over the 1974 and 1975 yearly series, as well as the four month series blocks, April-July and Sept. - Dec., 1974, considered in the report. The cross-coast wind vs. sea level comparisons, at coincident or nearby sites, indicate more selective coherence bands. One of the potential hazards which was noted in the report was that the Wilmington tide gauge is located 43.4 km from the mouth of the Cape Fear River Estuary, a tidally influenced coastal plain estuary which undoubtedly has a sea level response signature very different from that of an open, coastal station. Consequently, intercomparison of sea level at WIL and any other station, except for one at the mouth or between, in the Cape Fear River Estuary, as was done by Brooks (1978) to confirm the existence and southerly propagation of continental shelf waves, must be done with appropriate reservation.

Recently, Chao and Pietrafesa (1979) reviewed the shelf wave literature and have determined that the phenomena are probably not existent on the coast of the Carolinas, or if these waves do exist, they are of minor importance. These authors considered subtidal sea level fluctuations of four tide-gauge stations along the Carolina Capes coast (Beaufort, Wilmington, Cape Fear and Charleston) and their relations to atmospheric forcing.

Their analyses of cross-spectra of barometrically adjusted sea level between station pairs negate earlier concepts of southward propagating shelf waves. The cross-spectra of alongshore wind stress versus adjusted sea level fluctuations indicate that there is a retardation of set up/down of 6 to 12 hours at the Cape Fear coastal station (Wilmington). Therefore, these authors found that earlier observations (Mysak and Hamon, 1969; Brooks, 1978) of southward phase propagation in Onslow Bay were most likely the consequence of the retardation of set up/down at the Cape Fear, rather than of a continental shelf wave. Further detailed anlaysis shows that both the direct frictional set up/down and Ekman set up/down were present at Carolina coastakl stations, while the former was more significant near Cape Fear due to the excursion of shoals there, provided the right mechanism for the retardation of set up/down was observed. This paper also points out that, in cases where the amplitude of set up at the coast is comparable to sea level variation due to shelf waves, inferences of wavelength and phase speed, etc., based on the use of the cross phase between two time series, could be misleading.

Lee (1978) showed from cross-spectra of Savannah winds, for the winter period, that variations occurring near the common periods of 2.5, 3.5, 5 and 10 days were highly coherent. Careful classification of wind events indicates that the periods of these coherent wind oscillations were related to the passage time over the shelf of cold fronts and winter cyclones. As Pietrafesa, et al. (1978a) showed, the forcing from these wind events should be nearly in phase over alongshore distances on the order of 100 to 200 km. This effect is clearly noted by Lee (1978) in a zero phase difference in current fluctuations in alongshore, mid-shelf moorings. At Lee's mid-shelf moorings, located in 435 m of water, cross-shelf and alongshelf components were only marginally coherent at periods of about 2.5 and 5 days. At the 2.5 day period v led u by about 90° in-phase and could be associated with a traveling wave. However, u and v modulations with 5 day periods were very nearly in-phase, indicating that both components are forced simultaneously by the same process. This is further substantiated by the along-shelf coherence. The v-component was found to be highly coherent over the 90 km mooring separation distance in both upper and lower layers for all periods greater than 2 days with nearly zero phase, thus requiring a common, in-phase forcing. The u-component was only significantly coherent at periods of 2.5 days in the upper layer and about 3.3 days near the bottom, with the northern mooring leading by 90° in-phase. This suggests that cross-shelf fluctuations with periods of 2.5 to 3.3 days traveled southward at 120 to 150 $cm.sec^{-1}$ and wave lengths of 330 to 370 km. Temperature variations were also coherent at only the 2.5 day period, over the 90 km separation, with very nearly zero phase, for both layers. Vertical coherence computed over the 10 m separation between top and bottom instruments at mid-shelf was extremely high for all periods, > 2 days in u, v and T with zero phase.

Along the shelf break the offshore surface Ekman flux associated with northward winds may at times generate an eastward meander of the Gulf Stream cyclonic front and upwelling of cooler, deeper Gulf Stream waters along the slope. Since the Gulf Stream is displaced further offshore, a decrease in northward alongshore current speed occurs nearly simultaneously with the decrease in temperature brought about in upwelling. This is different than a pure wind-driven upwelling response, which in the absence of a Gulf Stream would generate a baroclinic alongshore jet near the shelf break and an increase in northward current speed.

Southward wind episodes produce the opposite response, i.e., onshore mass flux in the surface Ekman layer and offshore flux in the bottom layer, set-up of sea level along the coast, southward geostrophic flow in the shelf interior waters, an onshore Gulf Stream meander and associated downwelling, causing increased temperatures and northward current speeds along the shelf break.

For summer conditions, Lee (1979) indicates that there was a considerable amount of visual coherence between wind and mid-shelf currents. Cross-spectra of along-shelf wind and current from the upper current meters of the shorter period combined DOE and BLM array and the longer "Summer 77" period. Cross-spectra of alongshelf wind and current from the mid-shelf location show significant coherence over the period band of 3 to 10 days with the wind leading by less than 1 day. At the 40 m isobath there was an additional coherent peak at about the 2 day period. Alongshelf currents at the outershelf locations did not show any significant coherence with the wind. Alongshelf currents at mid-shelf (AT) recorded over the longer period showed a similar high correlation with the wind as during the "short-term" measurements. Alongshelf currents at the shelf break also show a similar lack of coherence with alongshelf wind during the short and long computation periods. By comparison, Lee (1978) showed that during winter, cross-spectra of alongshore wind and current from meters located 17 m from the surface at the mid-shelf location show high coherence in the 2.5, 3.5 to 5, 7 to 12 day period bands with the wind leading by about 10 to 24 hours. Alongshelf current fluctuations in the lower layer showed even stronger correlation to the v wind. Cross-shelf current variations were coherent with u winds at only 2.5 day periods with a 10 hour lag in the upper layer, and at 3.3 day periods which were 180° out of phase with the wind in the lower layer. Cross-spectra of currents and temperature measured at the shelf break indicated that the only significant coherence found for the upper layer v-component current fluctuations was with the u-component winds at periods of about 3 to 4 days and 8 days with wind leading by 6 to 16 hours. In the lower layer alongshelf current modulations at periods of around 8 and 20 days were coherent with v winds with the wind leading by around 48 hours. At the 2.5 day period v current was coherent with u wind and very nearly in phase. Cross-shelf near bottom current variations were significantly coherent with u winds at the 5 day period, with wind leading by about 40 hours. Near bottom temperature fluctuations were highly coherent with the cross-shelf winds at periods of 5 days, where temperature changes were almost 180° out of phase with the wind, and 3 to 3.5 days with wind leading by about 24 hours. Bottom temperature variations were also coupled to alongshelf wind deviations at periods of 5 days with temperature leading by about 90° and 8 to 10 days, where temperature oscillations were nearly 180° out of phase with the wind.

The percent of the sub-tidal current variance due to wind has been estimated by both Lee and Pietrafesa to be essentially 0 to 16% at the shelf break. Thus along the shelf break, low frequency current fluctuations were primarily generated by Gulf Stream perturbations, such as wavelike meanders, instabilities and eddies. However, these events may have initially been caused by wind forcing. Sub-tidal current oscillations at the 45 m isobath were also predominantly Gulf Stream produced, but local wind forcing accounted for about 30% of the alongshelf variability in the upper layer, and 36% in the lower layer. At mid-shelf, low frequency cross-shelf motions were completely Gulf Stream generated and the alongshelf variability was about equally produced by wind and Gulf Stream forcing in both upper and lower layers. Nonetheless, upwelling favorable winds appear at times to be visually well-correlated with the large decreases in lower layer temperature near the shelf break. The following model of a wind-forced, upwelling meander is proposed to account for a significant portion of these observations. Winds from the south at the start of a cold front cause an offshore Ekman flow in the surface, forcing the Gulf Stream surface front eastward, thus generating an eastward meander. The resulting wave is initially phase-locked with the wind so a rather large meander can result. In response to the offshore surface flow upwelling of cool deeper Gulf Stream water occurs along the slope. Since the Gulf Stream is further offshore, a decrease in northerly alongshore current occurs. So, an offshore meander of GSF produces a decrease in both temperatures and alongshore current speeds at the shelf break. As the wind shifts from south to north (passage of a cold front), an onshore surface Ekman flow develops which forces an onshore meander and downwelling along the shelf break. During an onshore meander the Gulf Stream cyclonic front moves closer to the shelf break, increasing the northerly current speeds there. The meander may be either directly wind-forced as was observed by Webster (1961a) off Onslow Bay, or due to a propagating wave that may have been wind-generated (Brooks and Mooers, 1977).

When the speed of the southward propagating shelf wave is less than the mean northward speed of the Gulf Stream, it becomes advected northward so that the observed direction is to the north in the upper layer near the shelf break. The signature in a current/temperature record from the shelf break would be the same for either process.

Atmospheric cooling of shelf waters has been noted by Pietrafesa (1979). A major cold air mass outbreak on January 10, 1977, produced a dramatic drop of mid- to inner-shelf temperatures down to a depth of 25 m. The drop in T was shown by Pietrafesa to have been caused by a downward diffusion of cooled surface waters. A vertical diffusion coefficient of 32 $cm^2.sec^{-1}$ was computed. The cooling effect of this meteorological event seems to have lasted until March throughout the whole SAB.

A.1.3 Shelf Variability at Frequencies Higher Than Half Cycle/Day (Tidal Forces)

The astronomically forced semi-diurnal tides propagating shoreward from the deep ocean are a dominant feature observed throughout the SAB. Between these semi-diurnal tides and the lower frequency weather continuum, three processes occur in varying degrees across the shelf: diurnal tides, inertial oscillations and sea breeze. These all have time scales of roughly one day. Processes occurring at frequencies higher than the semi-diurnal tides include internal inertia-gravity waves, edge waves and surface gravity waves.

The semi-diurnal current amplitude fluctuation evidently controls a large portion of the current variability. Redfield (1958) analyzed sea level records along the east coast and concluded that the principal lunar semi-diurnal tide on the continental shelf is a co-oscillation caused by the reflection of an incident oceanic wave by the coast. The portion of the oceanic wave transmitted onto the shelf reflects off the coast resulting in an increase in the tidal amplitude with distance from the continental slope. This type of reflected inertia-gravity wave is called a Poincare wave. It has a maximum elevation slightly seaward of the coast and the associated water particle motions in the horizontal plan are elliptical, clockwise polarized, and oriented with the semi-major axis along the direction of propagation. The ratio of semi-minor to semi-major axes is theoretically predicted to be a pendulum day ($2\pi/f$) divided by the wave period (in this case 12.41 hours). Thus the predicted axis ratio is 0.559 at the latitude of 32° 38'. From raw and/or 3 HLP* data presented by either Pietrafesa

(1979) or Lee (1979), it is clear that the amplitude of the tidal current decreases with depth. This effect may be attributed to bottom friction. A small phase shift (less than 1 hour) also occurs between the upper and lower tidal current due to bottom friction. If one defines an effective pressure gradient as the resultant of the pressure gradient and tide generating forces, then the currents at any depth attain their maxima when the frictional forces are in balance with the effective pressure gradient. At this phase the effective pressure-gradients will be decreasing so the currents will attain their maxima before the effective pressure-gradients vanish. The frictional forces arise from the bottom. If it is assumed that those near the bottom are greater than those higher up, then it follows that the bottom-currents will reach their maxima earlier than the higher currents and consequently all phases of the bottom currents will occur earlier than corresponding phases of the higher currents.

Using an energy fraction versus frequency representation, one can see quite clearly what fraction of the total variability is in the high versus low frequency end of the energy spectrum. Current data collected 17m from the surface in water depths of 75m (Site J), 45m (Site C), and 38m (Site P) in Onslow Bay (Pietrafesa, 1979) and in 75m (Site B) and 30m (Site A) of water offshore of Savannah (Lee, 1979) are shown in Figures A-5 and A-6. It is clear that the shelf proper moorings show dominance of the semi-diurnal tide in the cross-shelf direction while the shelf break is dominated by low frequency variability. Table A-1, from Pietrafesa (1978) shows the amplitudes of all of the tidal components. The description above indicates that a model for a frictionally modified Poincare wave will reproduce the characteristics of the dominant M_2 tidal component as well as the S_2 tidal component for the SAOS Region.

This semi-diurnal tide model can be expressed in the following manner:

(1) $U_t - fv = g\zeta_x$ in the on/off direction, and

(2) $V_t + fu = g\zeta_y$ in the alongshore direction, and

(3) $P_z = - g\rho$ in the vertical.

where u and v are the "on/off" and "along" depth averaged current components, ζ is the surface elevation, g the gravitational acceleration, p the pressure, f the Coriolis parameter, ρ the density and subscripts denote partial differentiation. The time averaged depth is h(x,y) and the vertically integrated equation of continuity is:

$$(4)\quad (hu)_x + (hv)_y = \zeta_t$$

Next, assuming $\xi = G(x)\cos(ot - ly)$, then (1) and (2) result in

$$(5)\quad u = \frac{g}{(f^2 - \sigma^2)}(\sigma G_x - flG)\ \sin(\sigma t - ly)$$

and

$$(6)\quad v = \frac{g}{(f^2 - \sigma^2)}(fG_x - \sigma lG)\cos(\sigma\, t - ly)$$

Equations (5), (6) and (4) can now be combined to yield the relation

$$(7)\quad (hG_{xx}) + \frac{((\sigma^2 - f^2)}{g} - \frac{flh_x}{\sigma} - l^2h)\ G = 0$$

This is the governing equation of the Sturm-Liouville type and with the conditions of G remaining bounded as X ∞ , and with no singularities at x = 0 then the system is matrhematically proper. If the coefficient preceding the G term is negative, then trigonometric solutions are available, and furthermore, if (for the sake of simplicity), h is constant and if σf , the plane waves occur for $K^2 > 0$, where G(x) is proportional to e^{ikx} and $l \gtrless 0$. Inclusion of variable, regularly deepening h to seaward presents no major problems in the theory. These plane waves are called Poincare waves and the M_2 tidal component is an example of such a wave having a minimum elevation slightly seaward of the coast and an associated elliptical, clockwise polarized water particle motion in the horizontal plane. The semi-majoraxis of the tidal ellipse is oriented in the direction of wave propagation (See Figure A-7) and the ratio of semi-minor to semi-major axes is theoretically predicted to be the wave period, 12/(sin θ) in hours. This ratio is 0.563, 0.578 and 0.593 for latitudes of 33, 34 and 35 degrees north, respectively. The velocity data in Onslow Bay is certainly consistent (See Table

			M_2			S_2			M_4	
Record	Length* (h)	Orientation	Semi-Major ($cm \cdot s^{-1}$)	Axis Ratio	Orientation	Semi-Major ($cm \cdot s^{-1}$)	Axis Ratio	Orientation	Semi-Major ($cm \cdot s^{-1}$)	Axis Ratio
CT	1434	132	17.2	0.52	136	3.1	0.48	163	1.0	0.20
CB	1434	137	13.2	0.43	136	2.3	0.39	163	0.8	0.12
ET	1784	138	16.3	0.55						
FB	1784	152	6.8	0.26	163	2.1	0.29	136	1.3	0.25
AT	1123	138	14.5	0.45	143	2.3	0.52	073	2.4	0.35
BT	1123	115	11.9	0.44	091	2.5	0.68	073	1.8	0.20
CT	1123	133	9.4	0.55	136	2.5	0.52	165	0.6	0.10
ET	1123	137	13.3	0.52	137	3.1	0.48	019	0.8	0.40

* Length refers to duration of time series in hours for those current meter records.

TABLE A-1 TIDAL CONSTITUENTS IN ONSLOW BAY
OBSERVED DURING THE SUMMER OF 1976

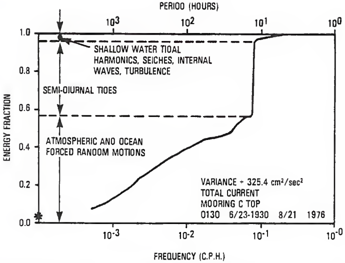


Figure A-5(a) **Energy Fraction vs. Frequency for C_{top} Total Current (Pietrafesa, et. al., 1978)**

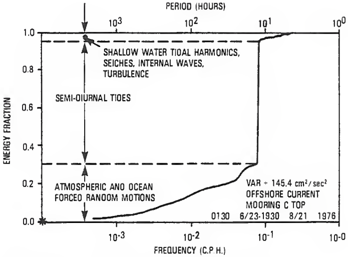


Figure A-5(b) **Energy Fraction vs. Frequency for C_{top} Offshore Current (Pientrafesa, et. al., 1978)**

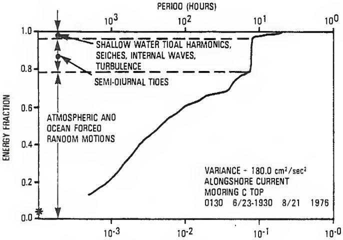


Figure A-5(c) **Energy Fraction vs. Frequency for C_{top} Alongshore Current (Pietrafesa, et. at., 1978)**

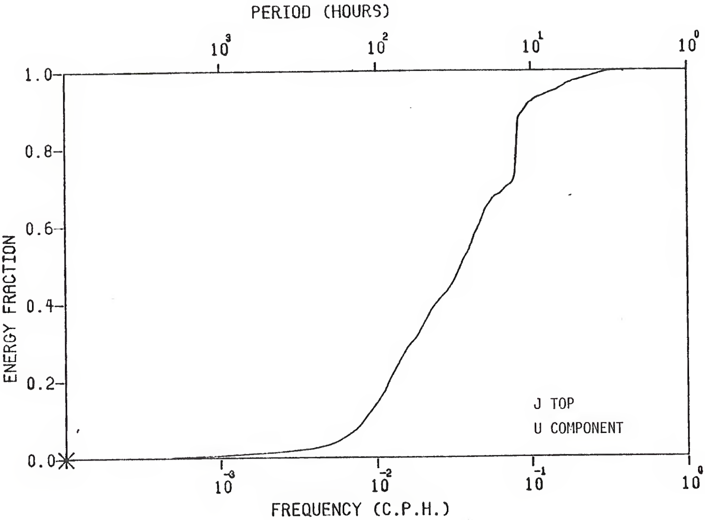


Figure A-5(d) Energy Fraction Diagram, U Component, Mooring J, Onslow Bay, N. C. (Pietrafesa, 1979)

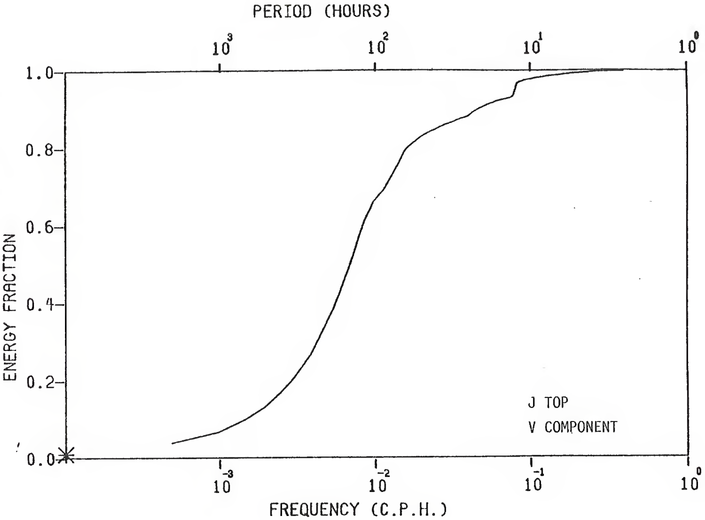


Figure A-5(e) Energy Fraction, V Component, Mooring J, Onslow Bay, N. C. (Pietrafesa, 1979)

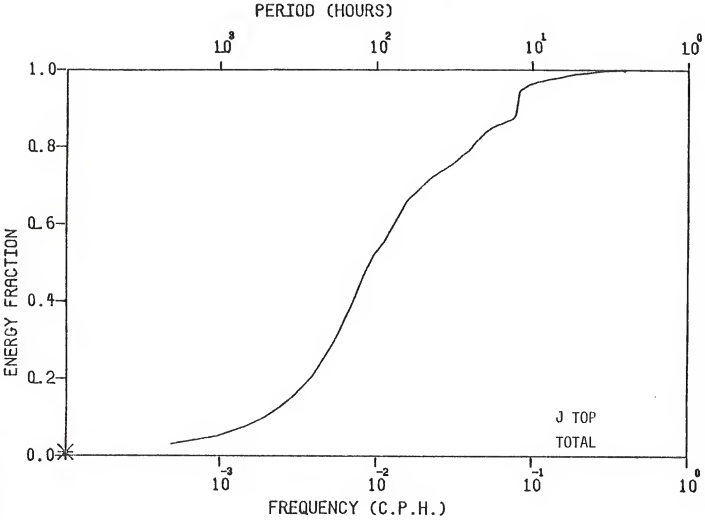


Figure A-5(f) Energy Fraction Diagram, Total Current, Mooring J, Onslow Bay, N. C. (Pietrafesa, 1979)

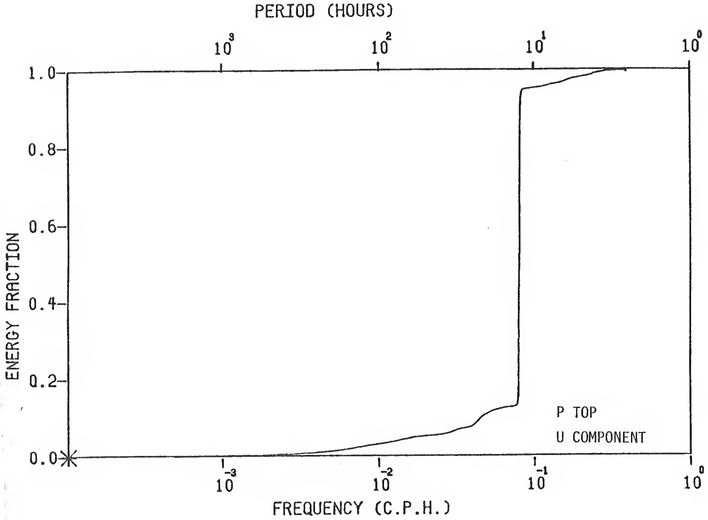


Figure A-5(g) Energy Fraction Diagram, U Component, Mooring P, Onslow Bay, N. C. (Pietrafesa, 1979)

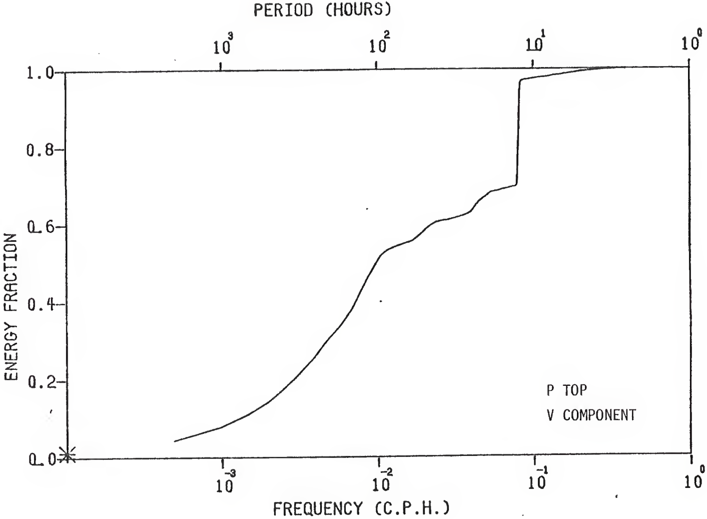


Figure A-5(h) Energy Fraction Diagram, V Component, Mooring P, Onslow Bay, N. C. (Pietrafesa, 1979)

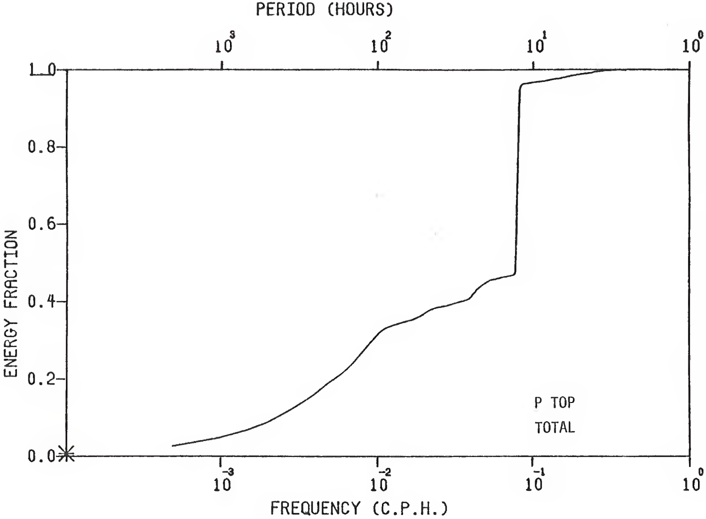


Figure A-5(i) Energy Fraction Diagram, Total Current, Mooring P, Onslow Bay, N. C. (Pietrafesa, 1979)

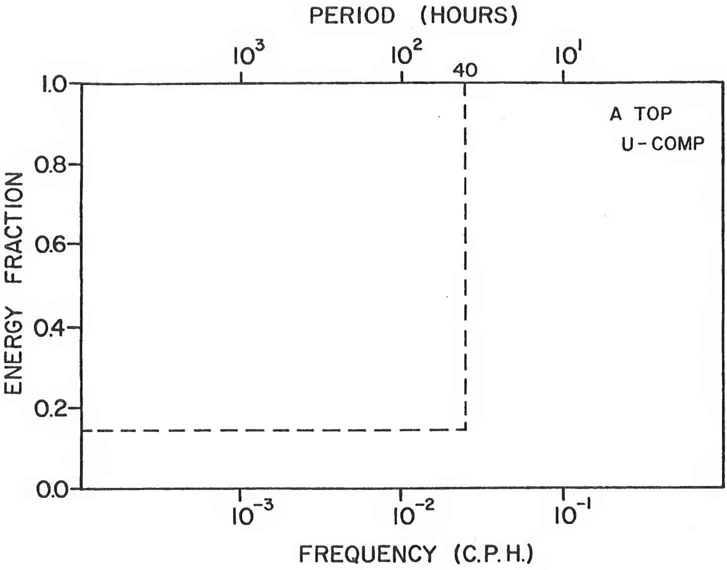


Figure A-6(a) Energy Fraction Depicting Percent of Energy in Bands Less Than and Greater Than 40 Hours, Offshore Savannah (Lee, 1979)

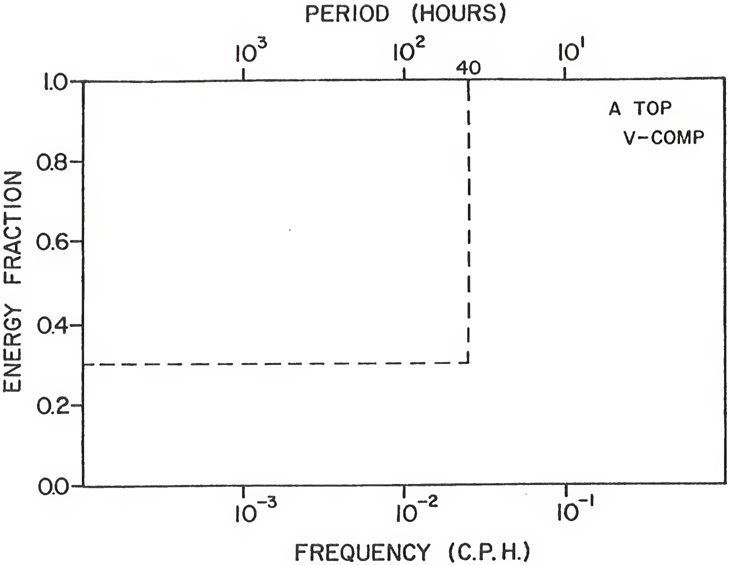


Figure A-6(b) Energy Fraction Diagram Depicting Percent of Energy in Bands Less Than and Greater Than 40 Hours, Offshore Savannah (Lee, 1979)

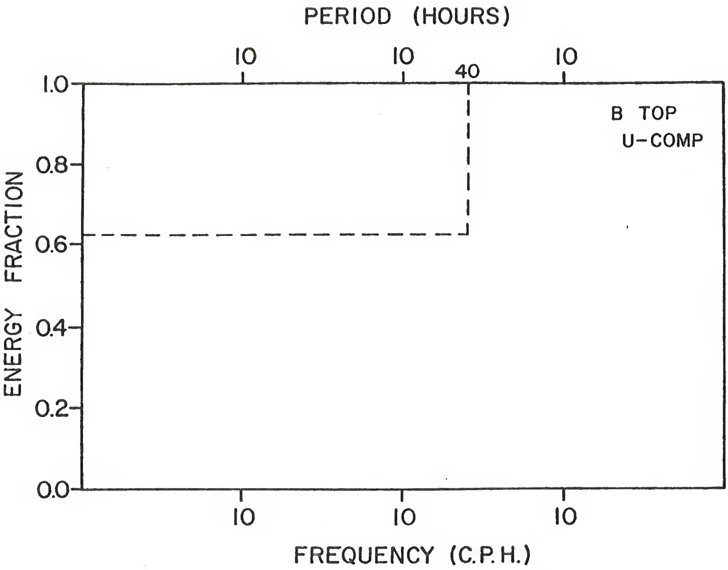


Figure A-6(c) Energy Fraction Diagram Depicting Percent of Energy in Bands Less Than and Greater Than 40 Hours, Offshore Savannah (Lee, 1979)

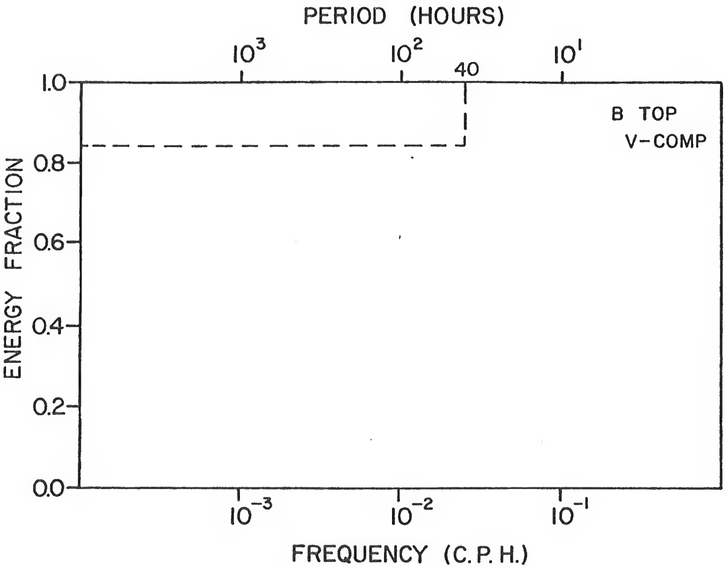


Figure A-6(d) Energy Fraction Diagram Depicting Percent of Energy in Bands Less Than and Greater Than 40 Hours, Offshore Savannah (Lee, 1979)

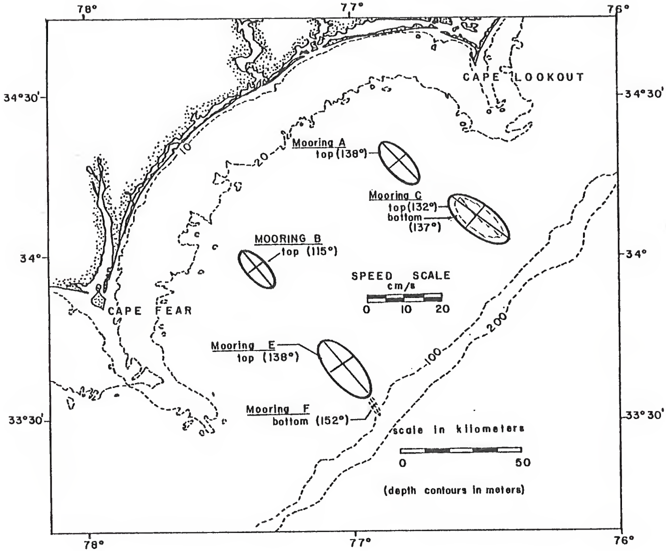


Figure A-7 Tidal Elipses For Summer

A-1) with both Redfield's view and with Poincare theory. It is of note that the ratios increase in the northerly direction, e.g., ET vs. CT, 0.52 to 0.55, and BT vs. AT, 0.44 to 0.45, which is also consistent with the wave theory.

The minor to major axis ratios are somewhat lower than that predicted by wave theory, especially at the bottom sensors, and in shallower water. Additionally, it is noted that the amplitude of the tidal current decreases with depth and the ellipse orientation is slightly rotated both from top to bottom and from mooring to mooring. Finally, a small phase shift (less than 60 degrees) is noted between the upper and lower hodographs, which can be explained with the inclusion of bottom friction in the above model, with the lower leading the upper (A more thorough discussion of the tidal forces and tide data can be found in Pietrafesa, 1978, "A progress report to the Department of Energy under Contract Number EY 76-S-09-0902", dated 1 March 1978; see specifically pages 225 to 234).

A.1.4 Thermohaline Circulation

Horizontal density gradients on a shelf can produce pressure gradients by inducing slopes in the sea surface (barotropic component) and isopycnals (baroclinic component), giving rise to a horizontal pressure gradient, which in turn can drive a flow. Because of the shallow depths on the shelf, vertical mixing from surface and bottom stresses should have a significant bearing on the flow in the winter and may lessen the effect of Coriolis force, which tends to turn the flow to the right. During stratified conditions, this effect may be more important. Horizontal density gradients result from temperature and salinity differentials across and along the shelf.

The characteristic features of the seasonal hydrographic data for shelf waters of the Georgia Embayment area: Winter - vertically homogeneous and horizontally stratified in both temperature and salinity; Spring - transitional; Summer - temperature stratified vertically and horizontally homogeneous, salinity both vertically and horizontally stratified; and Fall - transitional. Examples of these conditions are shown clearly in the BLM/VIMS Report (Ruzecki, 1974).

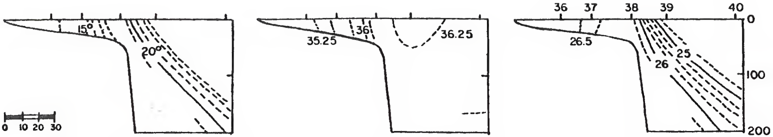
The opposing effects of temperature and salinity on density produce a seasonal change in the strength and sign of the horizontal density gradient, thus, a seasonal change can occur in the direction and intensity of the resulting flow. Winter increases wind-induced vertical mixing. Colder air temperatures tend to produce horizontal temperature and salinity gradients with opposite effects on density, which results in a weak, negative horizontal density gradient, producing a weak, northerly geostrophic flow. During the Spring transition period, freshwater runoff is at a maximum and forms a band of low salinity water near the coast, thus producing large cross-shelf salinity gradients. This effect combined with increased surface heating, which minimizes the shelf-Gulf Stream temperature differential, tends to produce a maximum positive horizontal density gradient. Since this is also a period when vertical mixing begins to diminish because of a decrease in surface wind stress, a density-driven flow develops, which tends to stratify the shelf. Lighter (fresher) water moves offshore on the surface, and denser (saltier) water intrudes onshore along the bottom. This Spring intrusion may also upwell cooler, deeper Gulf Stream waters having higher nutrient content onto the shelf for subsequent biological uptake. Bumpus (1973) indicated onshore, bottom flows for this period. Summer heating and diminished vertical mixing tend to increase the temperature contrast in the stratified layers. However, salinity still maintains enough horizontal difference to cause a downward slope in the isopycnals toward the west, which should result in a southward geostrophic flow. This finding also agrees with the Bumpus Summer drifter data. The Fall transition period is characterized by increasing wind-induced vertical mixing, which tends to break up the pycnocline, again producing vertically homogeneous conditions.

The seasonal hydrographic structure of the continental margin waters in the CC region, the northern end of the SAB, appear to be considerably more complex than what is considered typical for either Winter or Summer conditions on continental shelves in general or for the CC shelf in particular. The CC shelf has been hydrographically depicted as being vertically homogeneous and horizontally stratified during the winter months, and vertically stratified during the Summer period with appropriate Spring and Fall transitional periods. Low salinity coastal runoff and wind-driven incursions of Virginia coastal waters around Cape Hatteras into the CC zone, form a band of nearshore fresher water along the coast that accounts for the relatively large horizontal salinity gradients observed in the Winter. Winter cooling of surface waters and flux constraints over the shallow sloping bottom result in horizontal temperature and salinity gradients.

In the nearshore region, salinity can control the density distribution, producing a horizontal density gradient with lighter water near the shore. This condition will tend to develop a density-driven circulation with lighter water moving offshore along the surface and denser water moving onshore along the bottom. This effect is usually balanced or dominated by vertical mixing, which is normally strong enough in the Winter to overcome the density circulation, thus maintaining a well mixed water column. Figure A-8 clearly depicts the seasonal horizontal gradients, and offers striking testimony to the strength of the negative horizontal density gradients along the surface during Winter. The negative gradients would drive a flow onshore at the top and offshore at the bottom, except that an occasional positive offshore density gradient occurs in the near-bottom horizontal plane, which, in the presence of an insulated impermeable bottom, will drive a slow flow onshore in a bottom boundary layer.

The horizontal temperature gradient, under Winter conditions and as a function of relative strength, could either control the density or modify it in deference to the strength, of the salinity gradient, which fluctuates in intensity as an effect of the passages of the Winter cold fronts. The vertical integrals of negative horizontal density gradients can geostrophically drive a flow to the North. The vertical integrals of positive gradients, which are less evident in Winter, can induce a Southerly drift.

The Spring transition is essentially brought about by surface heating through insolation, but given the presence of a relatively large positive density gradient, which is now relatively enhanced, a gravitational circulation occurs with flow onshore near the bottom and offshore in the surface layer. The weak, alongshore density-driven flow now becomes southerly. During the Fall transition, the opposite response occurs to the baroclinic-geostrophic and gravitational density-induced forcing. This density-driven flow description agrees at least qualitatively with the slow, low frequency, density-driven flows on the Georgia shelf as discussed previously.

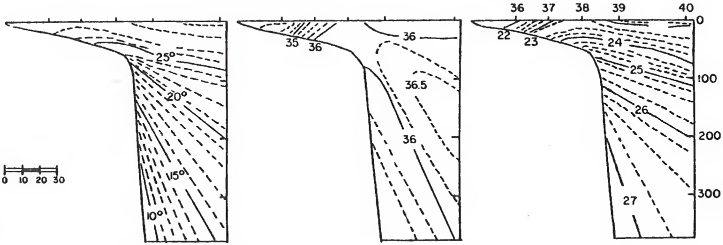


Cruise 5
January-February
1954

Temperature in °C.

Salinity in ppt.

Density (δ_T)



Cruise 7
June-July 1954

Temperature in °C.

Salinity in ppt.

Density (δ_T)

Figure A-8 Savannah Section, T. N. GILL Cruises (Ruzecki, 1974)

A basic difference exists between the density-driven current scenarios for CC and the Georgia Bight. South of Frying Pan Shoals, fresh water is input from the coastal boundary in a regular manner because of the estuarine systems that exist, so that a bona fide seasonality is prevalent. However, in the CC region, much less coastal input of fresh water occurs because of a lack of estuarine sources and the bands of Virginia Coastal waters, which are mechanically driven to the South of Cape Hatteras and occur on an intermittent basis, subject to the occasional passage of a "Northeasterly". Also, the Gulf Stream frequently penetrates across the shelf during all seasons, thereby introducing markedly different water masses from the resident shelf water masses and further complicating the picture.

The Bumpus drifter data suggest an onshore flow during the Winter, which seemingly contradicts the conceptual horizontal density gradient-driven circulation pattern that has been assumed; that is, the nearshore sinking of dense water in the presence of negative surface offshore density gradients results in a flow onshore at the top and offshore at the bottom. An onshore flow probably occurs at the bottom consistent with positive offshore density gradients in the presence of an insulated, impermeable bottom; an onshore flow occurs in the interior. The possible existence of an onshore bottom flow during the Winter enhances the ease with which the Spring transition can occur since during the transition the surface flow only reverses to an offshore direction, and the offshore interior flow relaxes. The onshore bottom flow conceptualization does not preclude the occasional existence of an offshore bottom flow, possibly in response to a northeasterly wind, in the form of downwelling at the coast and a subsequent cascading of cold, dense nearshore waters down the shelf.

The current meter data and bottom mounted pressure sensor data which have been collected in the SAB since 1975 are completely archieved at North Carolina State University, under the direction of Dr. L. J. Pietrafesa, and at the University of Miami, at the direction of Dr. T. N. Lee. Station locations and periods of observations are presented in Figure A-9 and Table A-2, respectively.

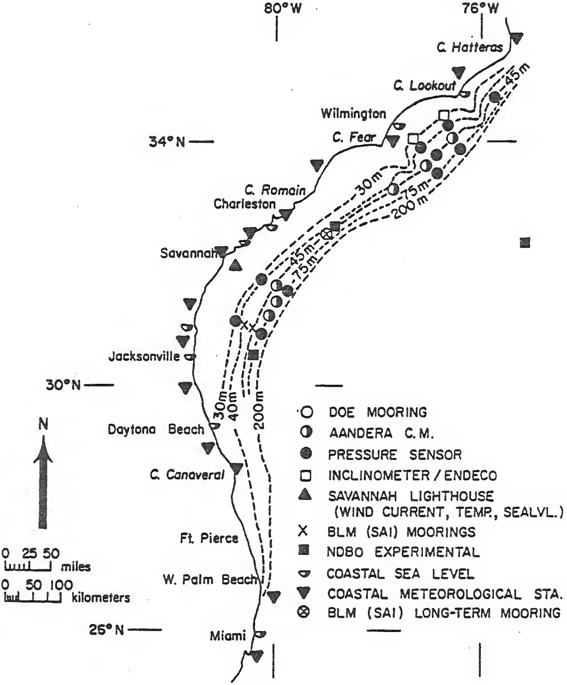
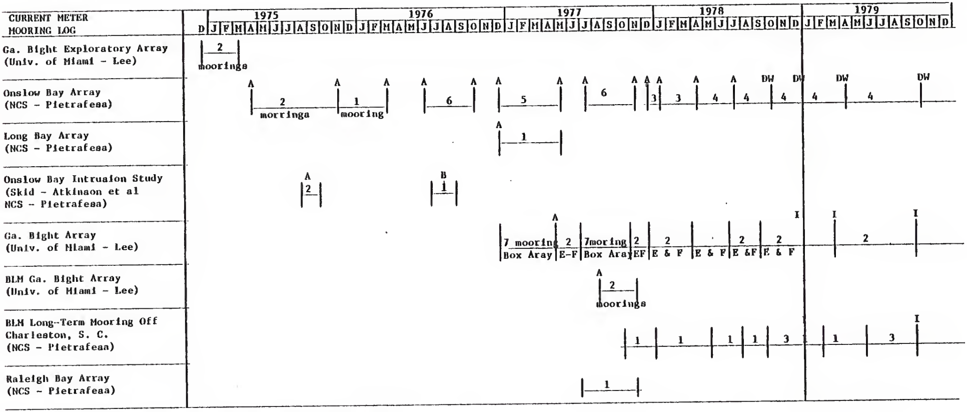


Figure A-9 Location of Moorings for Various Oceanographic Measurements in the SAOS Region



* NOTE: The letters above the time lines stand for ship names:
I - Iselin, A = Advance II, B - Bluefin, DW = DeWolf

The numbers stand for the number of moorings.

TABLE A-2. STATION LOCATION AND DURATION FOR CURRENT METER AND BOTTOM-MOUNTED PRESSURE SENSORS IN THE SOUTH ATLANTIC BIGHT.

A.1.5 Circulation Over the Blake Plateau

Circulation in the region of the Blake Plateau is poorly known. The Western-most two-thirds of the plateau is likely dominated by the Gulf Stream flow, while on the Eastern one-third of the Plateau region the anti-cyclonic Gulf Stream shear zone is encountered. Southerly flowing countercurrents and large cold core eddies spun-off from the Gulf Stream are encountered. Internal and bottom circulation over the Blake Plateau is largely unknown. Figure A-10 gives some published values for volume transport and annual variations in current speed for the Gulf Stream (Knauss, 1969 and Fuglister, 1951). Two studies have been conducted on the Blake Plateau circulation, one by Wimbush and Perkins (1977) and one by Ingham (1977). The Wimbush and Perkins effort consisted of two moored current meter arrays that were left in place for four (4) months along the precipitous eastern escarpment of the Blake Palteau. The primary finding of this study was that there was typically a strong Southerly flow along the Eastern margin of the Blake which was probably a local feature. Ingham's work was merely a summary of ship drift data for the surface flow and shows the Southerly feature also.

Prior to this work there was a study conducted by Heezen, et al (1966), on the bottom contour currents along the Blake Outer Ridge. Their map of this area (Figure A-11) indicates that bottom current measurements were made, although the text of their publication reveals that this work was based on data from a photograph of surface ripple marks in which a compass needle indicated their orientation. From these photos, the authors postulated a Southerly flowing bottom boundary current. Subsequent studies of the water masses and circulation patterns of the Blake-Bahama Outer Ridge (Amos, et al, 1971) showed that the Western Boundary Undercurrent (WBUC) flows with velocities up to 26 cm. sec^{-1} at the bottom, on the Eastern flank of the ridge. Although these measurements were not made directly over the Blake Plateau, they were cited for completeness, and to provide an idea of the relative magnitude and direction of bottom currents that could be anticipated in the Plateau area.

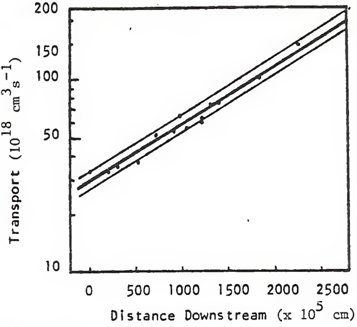


Figure A-10(a) Volume Transport as a Function of Distance Along the Gulf Stream (after Knauss 1969)

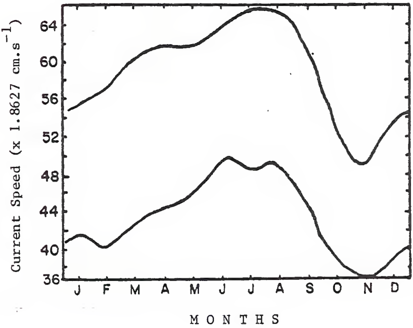


Figure A-10(b) Annual Variations in Current Speeds of the Gulf Stream (after Fuglister 1951)

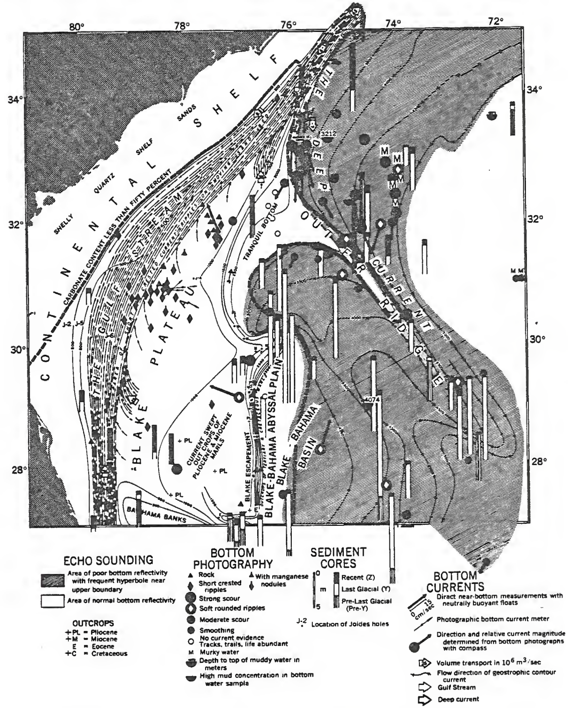

80°
78°
76°
74°
72°
34°
32°
30°
28°
CONTINENTAL SHELF
SHELLY
QUARTZ
SHELF
SANDS
CARBONATE CONTENT LESS THAN FIFTY PERCENT
THE GULF STREAM
BLAKE PLATEAU
TRANQUIL BOTTOM
CURRENT SWEPT OUTCROPS OF PLIOCENE & MIOCENE MARLS
BLAKE ESCAPEMENT
BLAKE-BAHAMA ABYSSAL PLAIN
BLAKE - BAHAMA BASIN
BAHAMA BANKS
THE DEEP OUTER CURRENT RIDGE
3212
4074
J-2
J-5
J-6
+PL
M
ECHO SOUNDING
Area of poor bottom reflectivity with frequent hyperbole near upper boundary
Area of normal bottom reflectivity
OUTCROPS
+PL = Pliocene
+M = Miocene
E = Eocene
+C = Cretaceous
BOTTOM PHOTOGRAPHY
Rock
With manganese nodules
Short crested ripples
Strong scour
Soft rounded ripples
Moderate scour
Smoothing
No current evidence
Tracks, trails, life abundant
M Murky water
Depth to top of muddy water in meters
High mud concentration in bottom water sample
SEDIMENT CORES
0
m
5
Recent (Z)
Last Glacial (Y)
Pre-Last Glacial (Pre-Y)
J-2 Location of Joides holes
BOTTOM CURRENTS
15 cm/sec
Direct near-bottom measurements with neutrally buoyant floats
Photographic bottom current meter
Direction and relative current magnitude determined from bottom photographs with compass
Volume transport in 10^6 m^3/sec
Flow direction of geostrophic contour current
Gulf Stream
Deep current

Figure A-11 Generalized Bottom Currents, Microphysiography, and Sediment Cores From the Blake Plateau (From Heezen and Hollister, 1971).

APPENDIX B

LIST OF PUBLISHED AND UNPUBLISHED SOURCES REVIEWED

A. Subjected to Further Analysis (Qual.)

B. Qualified with Roman Numerals Below and Dropped

I. Useful Background Information Only
II. Superseded
III. Analytical or Quasi-Analytical Model
IV. Homogeneous Models
V. Models Based on Empirical/Field/Laboratory Observations Only

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